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PARTICULATE COLLECTION EFFICIENCY MEASUREMENTS ON THREE ELECTROSTATIC PRECIPITATORS

Grady B. Nichols, et al

Southern Research Institute

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PARTICULATE COLLECTION EFFICIENCY MEASUREMENTS ON THREE ELECTROSTATIC PRECIPITATORS

by

Grady B. Nichols and Joseph D. McCain
Southern Research Institute
2000 Ninth Avenue, South
Birmingham, Alabama 35205

for

The M.W. Kellogg Company
1300 Three Greenway Plaza
Houston, Texas 77046

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The report gives results of a determination of the operating characteristics of three full-scale electrostatic precipitators (ESP's), made to provide definitive data on their performance. The measured performance of these ESP's was compared with the theoretically predicted efficiencies computed by an ESP mathematical model. Field measurements of total inlet and outlet mass concentrations, particle size distributions, and electrical data were used for these comparisons. Descriptions of the measurement procedures and the mathematical model are included. Two of the ESP's were at electric power generating stations; the third, at a cement kiln.

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ABSTRACT

The operating characteristics of three full scale electrostatic precipitators were determined to provide definitive data on their performance. The measured performance of these precipitators was compared with the theoretically predicted efficiencies computed by an electrostatic precipitator mathematical model. Field measurements of total inlet and outlet mass concentrations, particle size distributions, and electrical data were used for these comparisons. Descriptions of the measurement procedures and the mathematical model are included.

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SECTION I
INTRODUCTION

This report describes the results of tests conducted on three full scale electrostatic precipitators installed in commercial operations for the control of particulate emissions. These installations selected are considered to be representative of operating field precipitators in the U. S. The plants selected for tests are a station with a precipitator located prior to the air preheater; Gorgas Power Station, Alabama Power Company, Birmingham, Alabama; and the Citadel Cement Plant, Birmingham, Alabama.

The "hot side" precipitator represents an installation utilizing low sulfur western coal with the electrostatic precipitator installed between the air preheater and the economizer sections of the plant (hot side location). The Gorgas Power Station was selected as a representative power station for eastern coal with the electrostatic precipitator located downstream from the air preheater (cold side). The Citadel Cement Installation represents a reasonably modern installation on a cement kiln.

SECTION II
MEASUREMENT TECHNIQUES

The measurement techniques utilized for providing the required field data are discussed individually below. The methods utilized follow standard techniques for the mass train measurements. Special measurement techniques were utilized in the measurement of particle size, gas analysis, and resistivity.

MASS CONCENTRATION MEASUREMENTS

The inlet and outlet particle mass loadings were measured with the EPA Method 5 technique. The sampling procedure followed was that described in the Federal Register, Vol. 36, No. 247, December 23, 1971. The probe cleaning and sample extraction procedure is described in detail below since it deviates from the recommended procedure.

EPA Mass Train Cleaning Procedure

Cleaning of the "front half" of the EPA Method 5 Mass Train is extremely important in determining the particulate concentration of gas streams. Frequently the majority of the particulate sampled from the gas stream will be collected in the probe and associated glassware and never reach the filtration media.

The following cleaning procedure has been demonstrated to be very effective in removing particulate captured in the mass train hardware and was the technique used during this test.

Probe Cleaning -

Immediately after removing the probe assembly from the gas stream both the tip and ball are taped to prevent gain or loss of particulate. The area where the tip if screwed to the probe body is washed to prevent outside contamination when the tip is removed. The tip is removed and rinsed with the wash bottle. After the initial wash the tip is brushed from both ends with a tube brush of correct size to remove "stuck" particles. The brush is washed to remove particles which become entangled in the brush fiber.

The probe body is held at a slight angle with the "front" end down and is washed from the ball end. This usually required two people (one to hold the collection container and one to actually wash the probe). After washing with rotation to assure wetting all walls of the liner, the probe is brushed with a steel or brass brush assembly similar to that used for cleaning guns. The brush is attached to a rigid assembly and forced from the ball to the "front". Care is exercised to allow the brush to exit the front slowly and thus reduce "splatter". With the brush extending through the probe, the brush is carefully rinsed to remove particulate from the bristles. After complete rinsing of the brush it is withdrawn from the probe. The probe is again rinsed and rotated to remove the last traces of particulate from the liner. The interior surface of the probe should have a bright metal sheen at all points after an effective cleaning.

Glassware Cleaning -

All glassware connecting the probe to the filter is carefully brushed and washed with distilled water with quantitative techniques to remove all particulate and transfer this material to the collected washings from the probe and probe tip.

PARTICLE SIZE MEASUREMENTS

The particle size distribution measurements were made by the use of both in-stack inertial impactors and optical counters for particle diameters greater than about 0.3 μm and by diffusional techniques with condensation nuclei counters in conjunction with diffusion batteries. The inertial impactors provide information on a mass per unit volume basis for particles with diameters of approximately 0.25 μm and larger. The optical technique provides information on the number per unit volume basis rather than a mass basis. The mass equivalent can be determined when the particle density is considered and a simple computation performed. A detailed description of the particle size distribution measurement equipment is described by Smith et al.[1] Therefore, only a brief discussion of the technique is given in this report.

OPTICAL AND DIFFUSIONAL MEASUREMENTS

The optical and diffusional measurements utilize a dark field photometer to detect the number of particles per unit volume in the view field. Extensive dilution of the gas stream being sampled is usually required because of the limitations imposed by the useful range of both the optical counter and condensation nuclei counter. Dilution ratios are selected to provide number

concentrations that fall within the dynamic range of the measurement equipment. As a general practice, checks of the linearity of particle count with dilution changes are performed to determine whether any anomalies resulting from condensation or other phenomena are occurring within the measurement system.

Due to limitations imposed by equipment availability, it is not possible to obtain simultaneous measurements at the precipitator inlet and outlet with the optical and diffusional measurements. However, the stability of the particulate concentration is in general sufficient to enable meaningful fractional efficiency data to be derived by first obtaining inlet data, and subsequently moving the equipment to the outlet to obtain the necessary data at that location.

The optical particle counter is calibrated with polystyrene latex spheres. The indicated diameter of the particulate in the stack gas can differ from the true diameter because of the difference in the refractive index of the material from that of polystyrene latex. In order to check the diameter obtained for the effluent, the diffusion batteries are used as sedimentation chambers, and the particle diameters obtained from the calculated sedimentation rates are compared with the indicated optical particle diameters. Figure 2-1 shows a sample comparison using values for particle density of 1.0 and 2.0 grams/cm^3 in the sedimentation calculations. Particle densities are estimated to range from about 1 to 4 grams/cm^3 in most field installations. The comparison indicates fair agreement between the sedimentation diameters, which are independent of refractive index, and the equivalent optical diameters. Figure 2-2 shows the optical and diffusional sizing system. The sampling probe is typically heated to avoid condensation.

Inertial Impactor Sizing Techniques

The inlet size distribution measurements were made with modified Brink impactors while the outlet measurements were made with modified Andersen Mark III impactors. The Brink impactor is a low volume flow device and the Andersen impactor operates at a relatively high volume flow. The selection of the low flow instrument for the inlet and a high flow instrument for the outlet allows near simultaneous testing at both locations. This difference in sampling rates is required because of the great difference in mass concentrations across a high efficiency collection device, typically on the order of a factor of 100.

The impactors are operated in the gas stream with the flow rates and sampling nozzles selected to provide near isokinetic sampling rates for both the inlet and outlet measurements. Thus, simultaneous inlet and outlet measurements are made with the impactors operating at approximately the same size distribution cut points to facilitate the interpretation of the data for evaluating the performance of the control device.

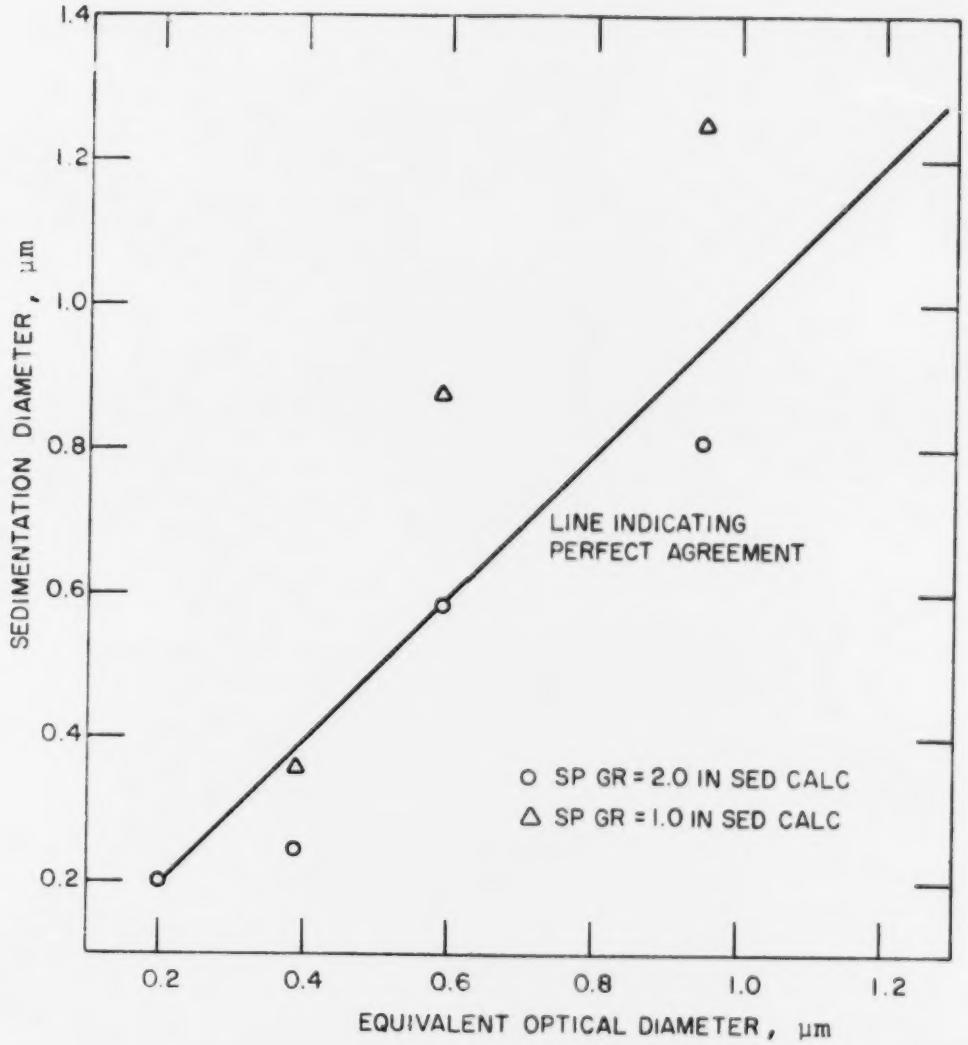


Figure 2-1. Comparison of sedimentation and equivalent optical diameters

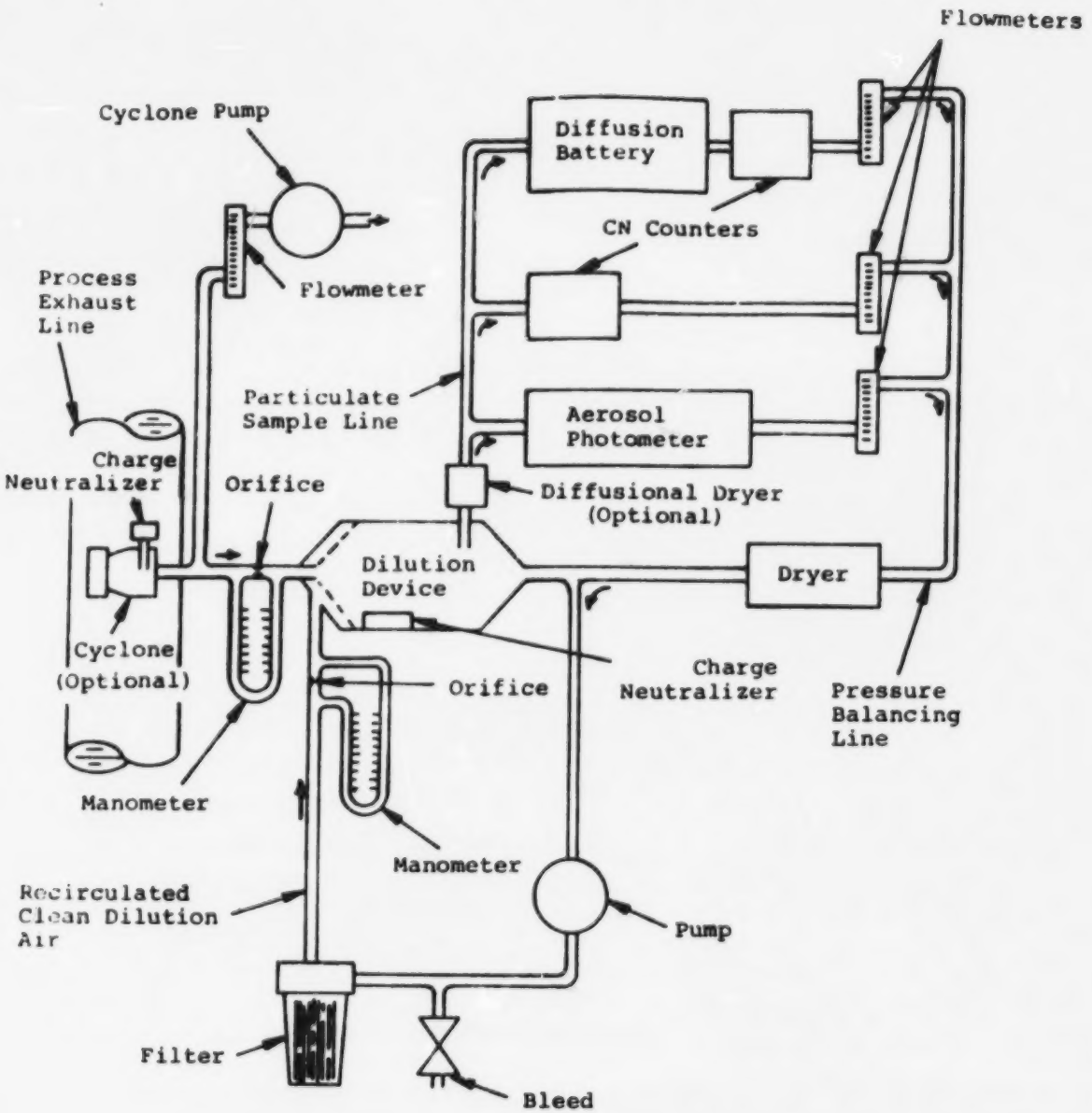


Figure 2-2. Optical and diffusional sizing system

Both types of impactors are operated with a back-up filter to collect the fraction of particles smaller than the last stage of collection. The Brink inlet impactor is equipped with a precollector cyclone that removes the large particle size fraction of the material before it reaches the actual impaction stages.

The operation of the impactors requires extreme care to assure that meaningful data are collected. The impactor substrates must be selected to minimize any reentrainment of previously collected particulate. Reentrained material would be transported by the gas stream to the next sequential collection stage. This phenomenon would cause errors in the measured size distribution.

The substrate material has the potential for chemical reaction with gas phase constituents. The material must be tested for gas phase reactions prior to their utilization in tests. The substrate material must be evaluated for gas phase reactions prior to use. This is described in more detail.

RESISTIVITY MEASUREMENTS

In-situ resistivity measurements are made with a point-to-plane electrostatic collection instrument. The device is inserted into the flue gas environment and allowed to reach near thermal equilibrium with the gas stream. The dust thickness gage is reset to zero and the measurement cell positioned for collection. A clean electrode voltage vs current characteristic is recorded. The current density for collection is selected and a dust layer is precipitated electrostatically. After collection, a second voltage vs current characteristic is recorded. This provides one measure of resistivity. The measurement electrode is then lowered to contact the dust layer and the layer thickness determined. The resistance of this known geometrical configuration (right cylinder) is measured. The resistivity is then determined from the measured resistance.

For the special case where the flue gas temperature exceeds 200°C, the resistivity is determined in the laboratory. A dust sample is collected in the field and the resistivity is measured according to the method described in the A.S.M.E. Power Test Code Number 28.

GAS ANALYSIS

The exit flue gas composition is determined by standard chemical techniques. The carbon dioxide and oxygen content are determined by standard Orsat techniques. The oxides of sulfur are determined by chemical techniques utilizing a conversion of sulfur dioxide to sulfur trioxide in a hydrogen perioxide solution and a condensation of the sulfur trioxide on the walls of a condenser. The concentrations of dilute sulfuric acid are determined by an acid titration utilizing a thorin indicator for the final determination. These measurements are conducted at intervals during the testing period.

The flue gas chemistry measurements are omitted in the power stations where the control device operates at temperatures in excess of 200°C. The sulfur trioxide does not materially influence the particulate characteristics at these relatively high temperatures.

PRECIPITATOR ELECTRICAL CHARACTERISTICS

The power supply secondary voltage and current values are recorded at intervals during the test program. If the precipitator is equipped with indicating meters, the values are recorded from these meters. If not, selected power sets are equipped with voltage dividers such that the secondary voltages will be known throughout the tests.

BOILER OPERATING DATA

The control room operating characteristics are noted at intervals during the test period. Such items as steam generation rates, electrical generation rates, fuel feed rates, etc. are recorded.

SECTION III
GORGAS POWER STATION - ALABAMA POWER COMPANY

INTRODUCTION

A test program was conducted at the Gorgas Power Station, Alabama Power Company, to evaluate the performance of the electrostatic precipitator installed on unit #10. This installation was selected as being representative of a well-designed conventional (cold side) precipitator collecting fly ash from an eastern coal. The primary objectives of this test program were to determine the overall collection efficiency of the unit, to evaluate the collection efficiency as a function of particle size and to analyze the performance of the unit by the use of the precipitator mathematical model.

ELECTROSTATIC PRECIPITATOR DESCRIPTION

Figure 3-1 illustrates the gas flow and precipitator arrangement. Some of the electrical sets were not operating on the B side precipitator, apparently due to broken corona wires; therefore, tests were conducted on the A side only. Each precipitator consists of two series section, each of which has 144 gas passages, with 0.229 m plate to plate spacing (9 in.). Each precipitator consists of 144 gas passages 9.14 m high (30 ft), 10.97 m long (36 ft), for a total collecting area of 28877 m^2 (311,000 ft^2 per precipitator. The precipitators each have twelve electrical sections arranged in series with the gas flow, such that the individual sections power 1/12 of the plate area and 1/12 of the length. Gas flow at full load ($\sim$700 MW) for each precipitator is about 520 m^3/sec (1.1×10^6 cfm) at 149°C (300°F). The specific collecting area at these conditions would be 55 $m^2/(m^3/sec)$ or 283 ft^2/1000 cfm.

RESULTS

The results from field measurements on this unit are given below.

Mass Loadings

The overall mass efficiency measurements were conducted by Scientific South, Inc., under contract with SRI. Figures 3-2 and 3-3 illustrate the velocity profiles obtained at the inlet and outlet sampling locations with preliminary pitot tube traverses performed on July 9, 1973. Inlet and outlet dust loading

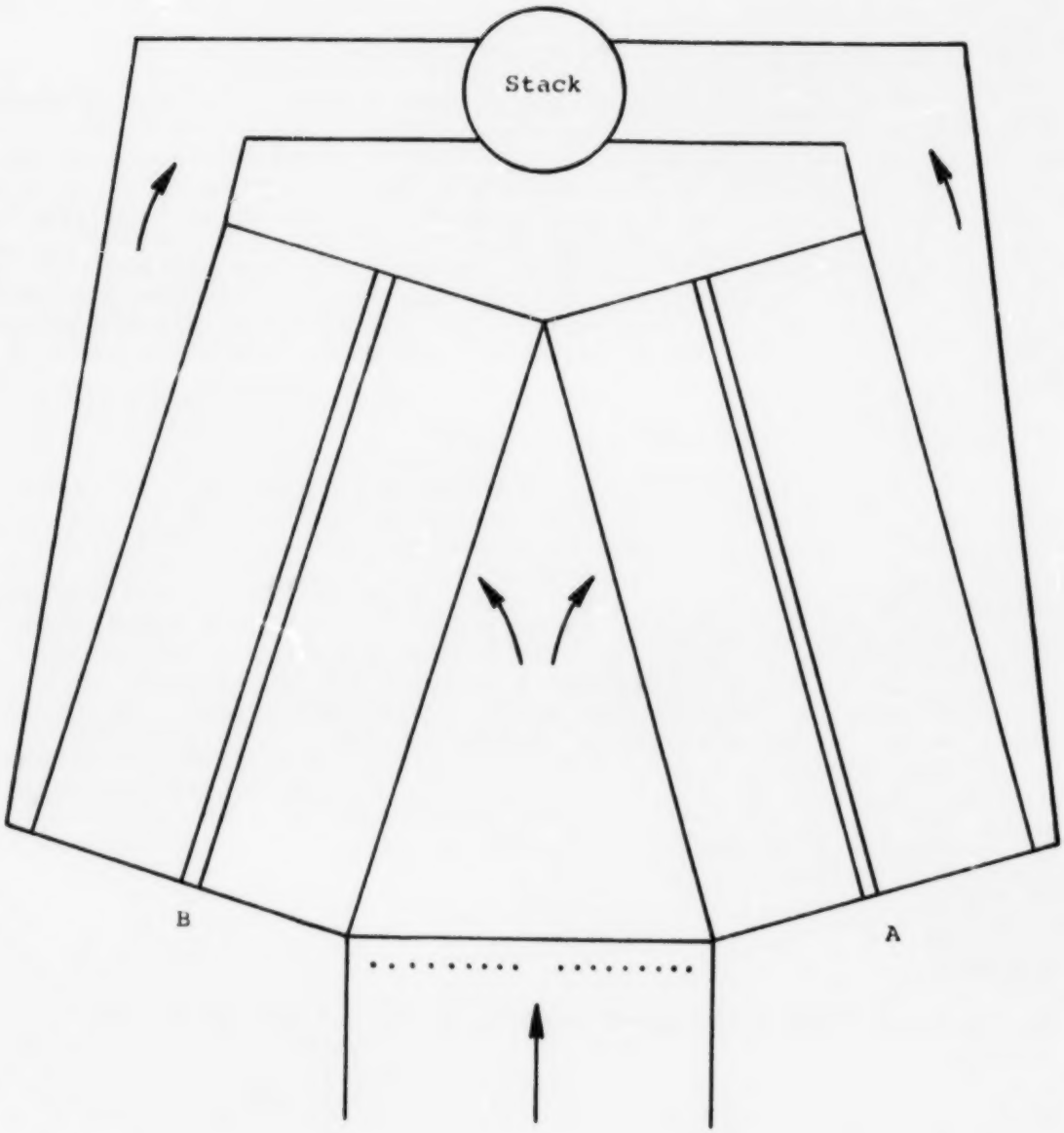


Figure 3-1. Precipitator Layout at Gorgas Unit 10.

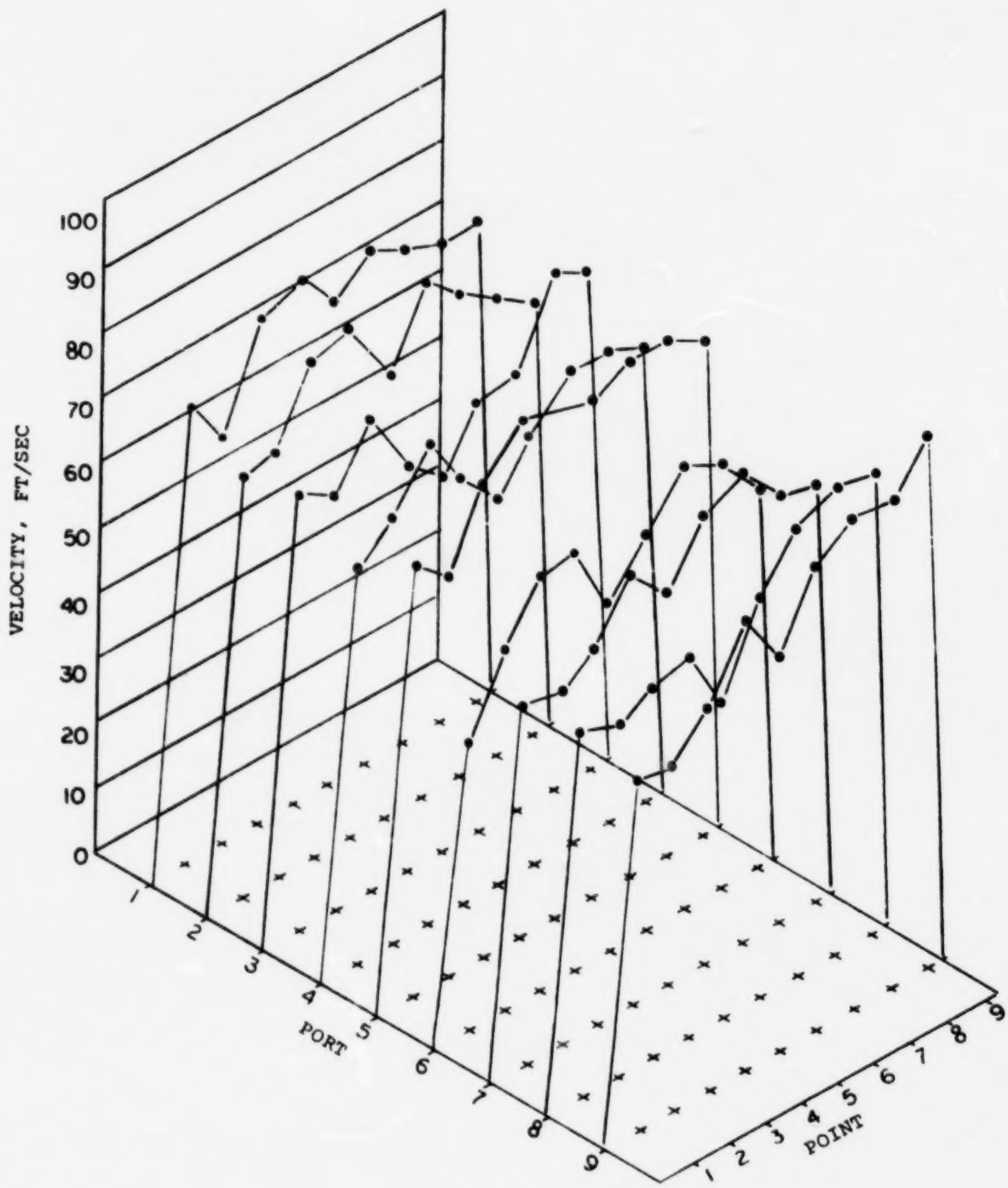


Figure 3-2. Velocity Traverse at Inlet.

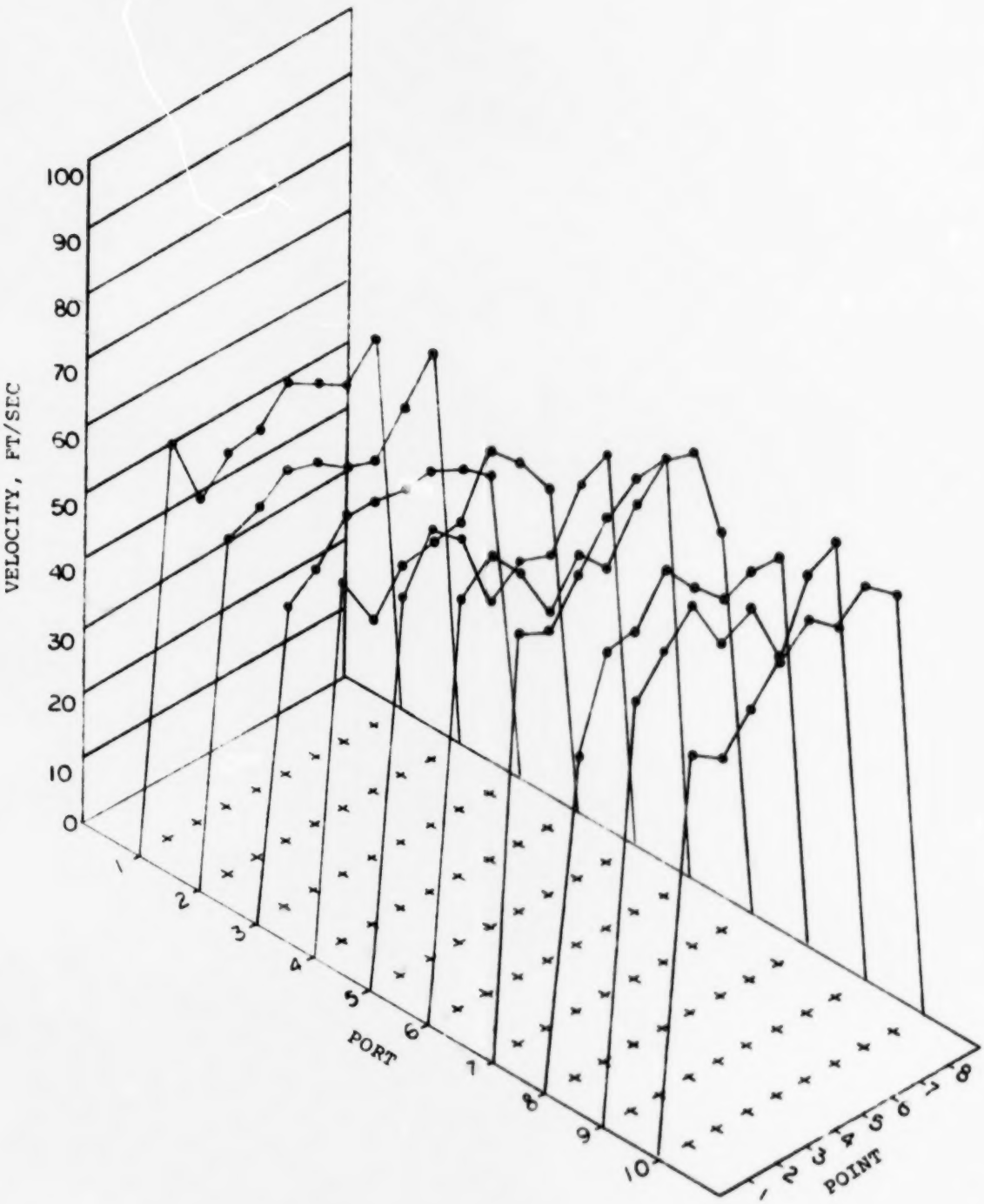


Figure 3-3. Velocity Traverse at Outlet.

measurements were conducted on July 10 and 11. The results of this work are given in Table 3-1. During the time period that the measurements were conducted, the generation rate was constant at 710 MW. Sampling was performed with an EPA approved sampling train manufactured by Research Appliance Corporation.

Fractional Efficiency Measurements

Tests using cascade impactors for particulate mass efficiencies as a function of particle diameter were conducted on July 10, 11, 12, 13, and 16. Inlet data were obtained with modified Brink impactors on the first four days of testing and outlet data were obtained with an Andersen impactor on all five days. Diffusional sizings with a series of diffusion batteries and two condensation nuclei counters were used to provide concentration and size distributions by number over the size range from about 0.005 μm to 0.3 μm. Relative concentrations on a number basis were measured using a Climet particle size analyzer equipped with a scanning pulse height analyzer and digital rate meter. Because of the high number concentration of small particles in the stack, dilution of the sampled gas stream by factors ranging from about 50:1 to about 1000:1 was necessary in order to obtain data with both the condensation nuclei counters and the optical particle counter. These data are given in Figures 3-4, 3-5, and 3-6.

Resistivity

The resistivity of the fly ash obtained in a previous test at a temperature of 165°C (330°F) is approximately 2×10^{10} ohm-cm.

Gas Analysis, Chemical Analysis and Coal Analysis

The results of the gas and coal sulfur content analyses are given below in Table 3-2.

Sulfur oxide analyses performed on July 10, 11, and 13 indicate that the SO_2 concentration dropped significantly, apparently as a result of decreasing sulfur content of the coal. There is some disagreement between the coal sulfur contents obtained from the plant records with those obtained by SRI. The samples which were analyzed by SRI were obtained after the coal was pulverized prior to injection into the furnace. Results from these analyses show proportionate agreement with the measured variation in SO_2 concentration. The current density of the precipitator also dropped significantly during the same time period, possibly as a result of the response of the power supplies to an increased tendency to spark arising

TABLE 3-1

DUST LOADING MEASUREMENTS AT INLET AND OUTLET OF PRECIPITATOR "A"

Date	Location Sampled	Temp., °F	Barometric Pressure		Gas Flow		Dust Load		
			m Hg	in. Hg	m^3/sec	ft^3/min	$Grams/m^3$	$grains/ft^3$	
7/10/73	Inlet	309	0.742	29.22	538	1.14×10^6	7.0200	3.0670	
7/10/73	Outlet	305	0.742	29.22	560	1.19×10^6	0.0291	0.0127[1]	
7/11/73	Outlet	317	0.745	29.34	538	1.14×10^6	0.0325	0.0142[2]	
7/11/73	Inlet	314	0.745	29.34	557	1.18×10^6	10.5000	4.5880	Average 4.5990
7/11/73	Inlet	313	0.745	29.34	566	1.20×10^6	10.5500	4.6100	

[1] Efficiency for 7/10/73 = 99.59%

[2] Efficiency for 7/11/73 = 99.69%

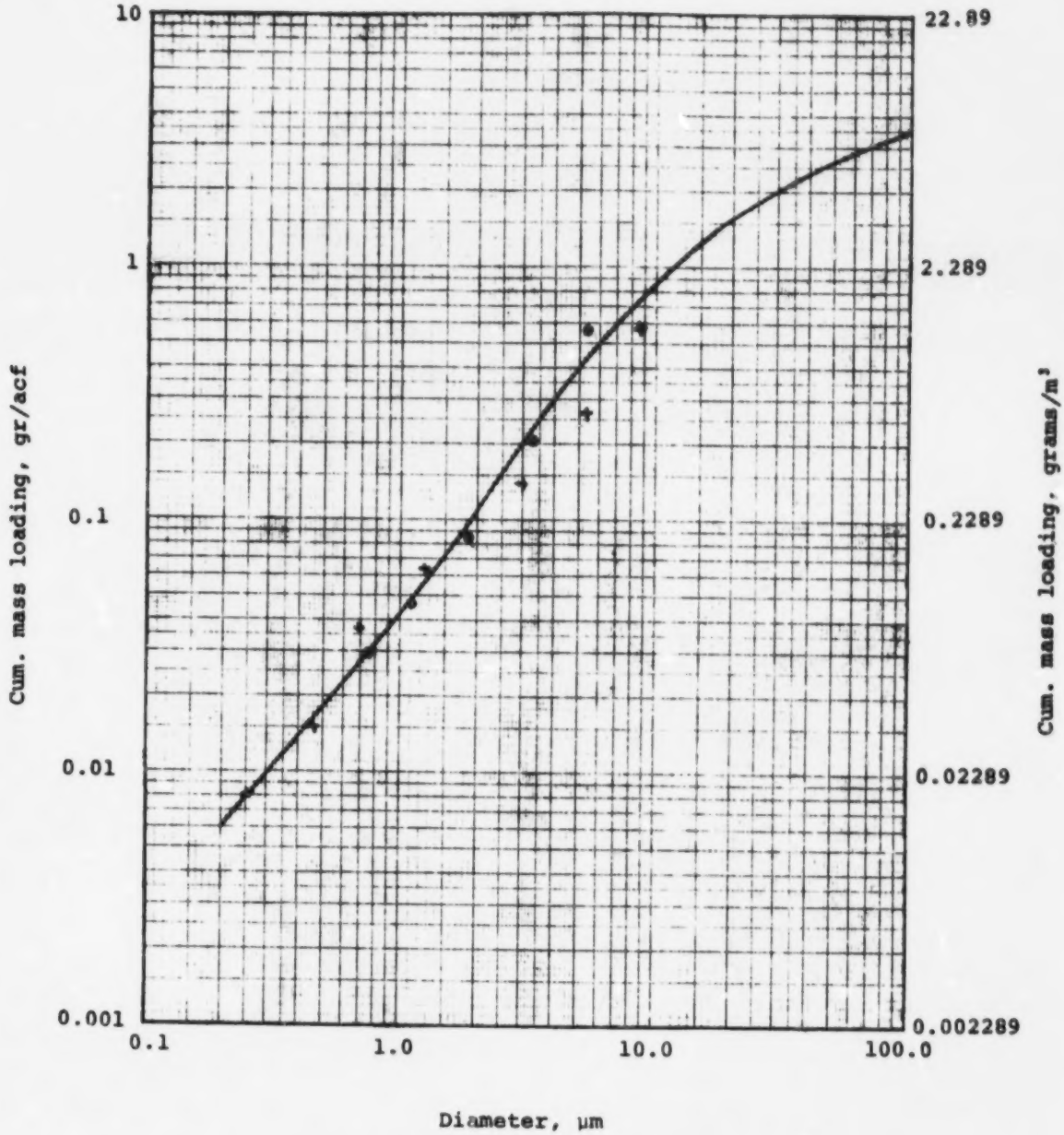


Figure 3-4. Inlet Size Distribution (0 and + represent different sampling conditions) Obtained from Modified Brink Impactor.

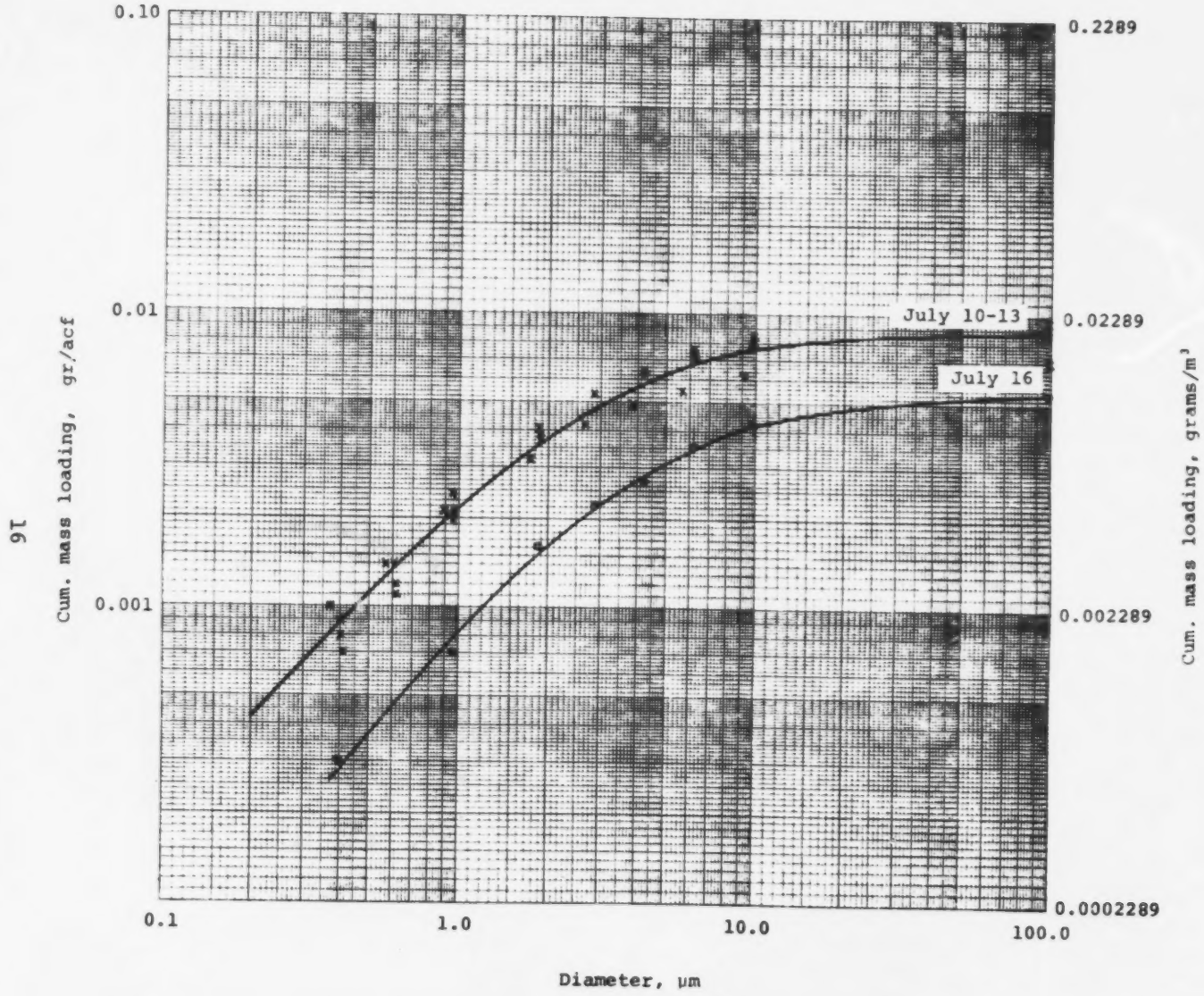


Figure 3-5. Outlet Size Distribution Obtained from Andersen Impactor.

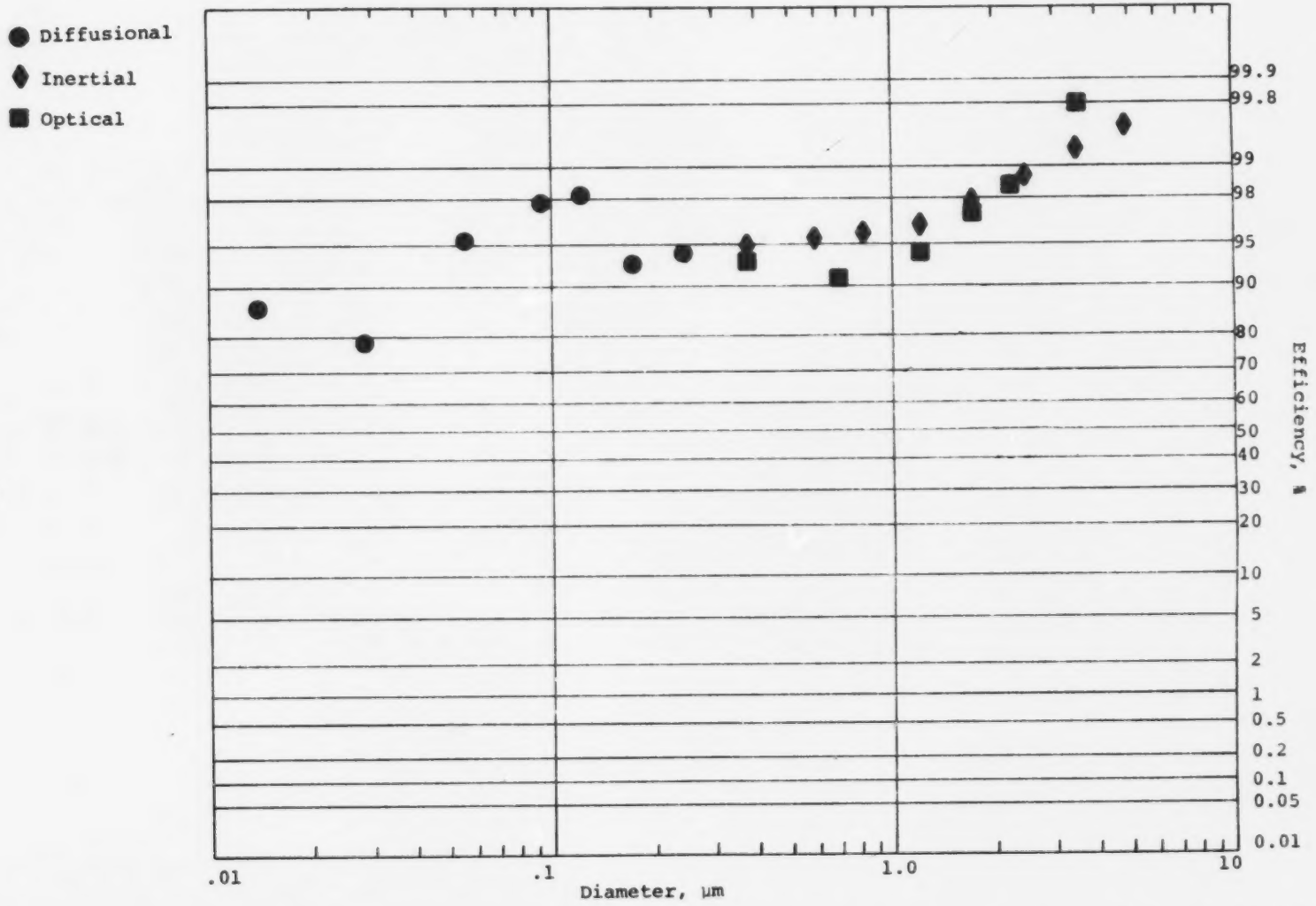


Figure 3-6. Measured and Computed Efficiency as a Function of Particle Size for Precipitator Installation at the Gorgas Plant of Alabama Power Company.

TABLE 3-2

SUMMARY OF DATA FROM GORGAS PLANT, UNIT 10, PRECIPITATOR A

Date	Flue Gas Composition				Overall Eff., %	Overall Current Density nA/cm²	Coal Sulfur Content, % (dry basis)		Load Megawatts
	SO_2 ppm by vol.	SO_3 ppm by vol.	H_2O % by vol.	O_2 % by vol.			Plant Log	SRI Sample	
7/9/73							1.19		
7/10/73	[1]1433	[1]3.8	[1]10.5	3.1	99.59	25.6	1.59	1.40	710
7/11/73				3.3	99.69	20.1	1.84	1.20	710
7/12/73	[1]1153	[1]6.0	[1]11.4			15.8	1.54	1.20	710
7/13/73	[2] 885	[2]2.4	[2]10.5			16.9	1.10	1.05	720
7/16/73						29.0	1.44	1.40	720

1. Measured at precipitator outlet.

2. Measured at precipitator inlet.

from electrical breakdown originating in a dust layer of increased resistivity. However, the chemical composition of the ash obtained from an exit hopper during the same time period suggests that sufficient sulfuric acid vapor was available in the flue gas to "condition" the finer size fraction (i.e., lower resistivity to an acceptable value). These data are presented in Table 3-3. Note that the outlet hopper samples give a slightly acidic pH when slurried in water, and that the soluble sulfate obtained from the hopper samples is significantly greater than that obtained from the traverse sample at the inlet. This is an indication of the increased surface area and sulfuric acid adsorption of the sample collected in the outlet hopper. Table 3-4 gives the overall composition of the ash obtained from the inlet traverse. Past experience that SRI personnel have had in studies of SO_3 conditioning programs suggests that this ash is relatively easy to condition because of the low CaO content.

Electrical Conditions

Figure 3-7 shows the voltage-current relationship obtained for one power set in the front and rear section of Precipitator B. These data were taken from the "B" side in order that measurements in progress on the "A" side would not be disrupted. The difference shown between the two power supplies may be caused, in part, by space charge suppression of corona current caused by the higher dust loading experienced by set 10BF, and, in part, by differences in electrode alignment.

Neither set shows any indication of back corona. Although operating current density is limited to an average of around 20 nA/cm^2 and the power supplies exhibit an increased sparking tendency as the sulfur content of the coal drops, the operation of this unit is not seriously impaired by high resistivity. A dust of excessively high resistivity often results in the occurrence of back corona at a lower voltage than the sparkover voltage, and would be indicated by drastically reduced precipitator performance and by the shape of the voltage-current relationships for the power supplies.

Performance Analysis

The measured performance of the electrostatic precipitator is compared with the computer projected performance as shown in Section VI with a discussion of the analysis program. The inlet particle size distribution data served as inputs to the computer program, together with the physical parameters of the precipitator. Projections of efficiency as a function of gas volume flow rate were generated with the model.

TABLE 3-3

pH and Soluble Sulfate of Ash Obtained From an Exit Hopper and an Inlet Traverse

Date	Time	[2] Hopper Sample		[3] Traverse Sample	
		[1] pH	Soluble SO_4^{-2} %	[1] pH	Soluble SO_4^{-2} %
7/10/73	1315	4.63	1.1		
7/10/73	1830	4.90	1.1		
7/10/73				8.0	0.4
7/11/73	1130	4.35	1.0		
7/11/73	1815	4.85	0.94		
7/11/73				8.5	0.5
7/12/73	1040	4.37	0.92		
7/12/73	1815	5.10	0.87		
7/13/73	1615	4.55	1.1		

1. Measurement taken after stirring for one hour a slurry of 30 ml distilled H_2O and 0.1000 g ash.
2. Obtained from a hopper near the outlet.
3. Obtained at inlet from traverse with sampling train.

TABLE 3-4

OVERALL COMPOSITION OF ASH SAMPLES OBTAINED FROM INLET TRAVERSE

Compound	Weight % 7/10/73	7/11/73
Li_2O	0.08	0.09
Na_2O	0.42	0.41
K_2O	2.4	2.3
MgO	1.1	1.1
CaO	1.8	1.8
Fe_2O_3	9.0	7.7
Al_2O_3	28.2	27.0
SiO_2	49.4	48.2
TiO_2	2.2	2.2
P_2O_5	0.59	0.50
SO_3	0.35	0.52
Loss On Ignition	5.2	8.3

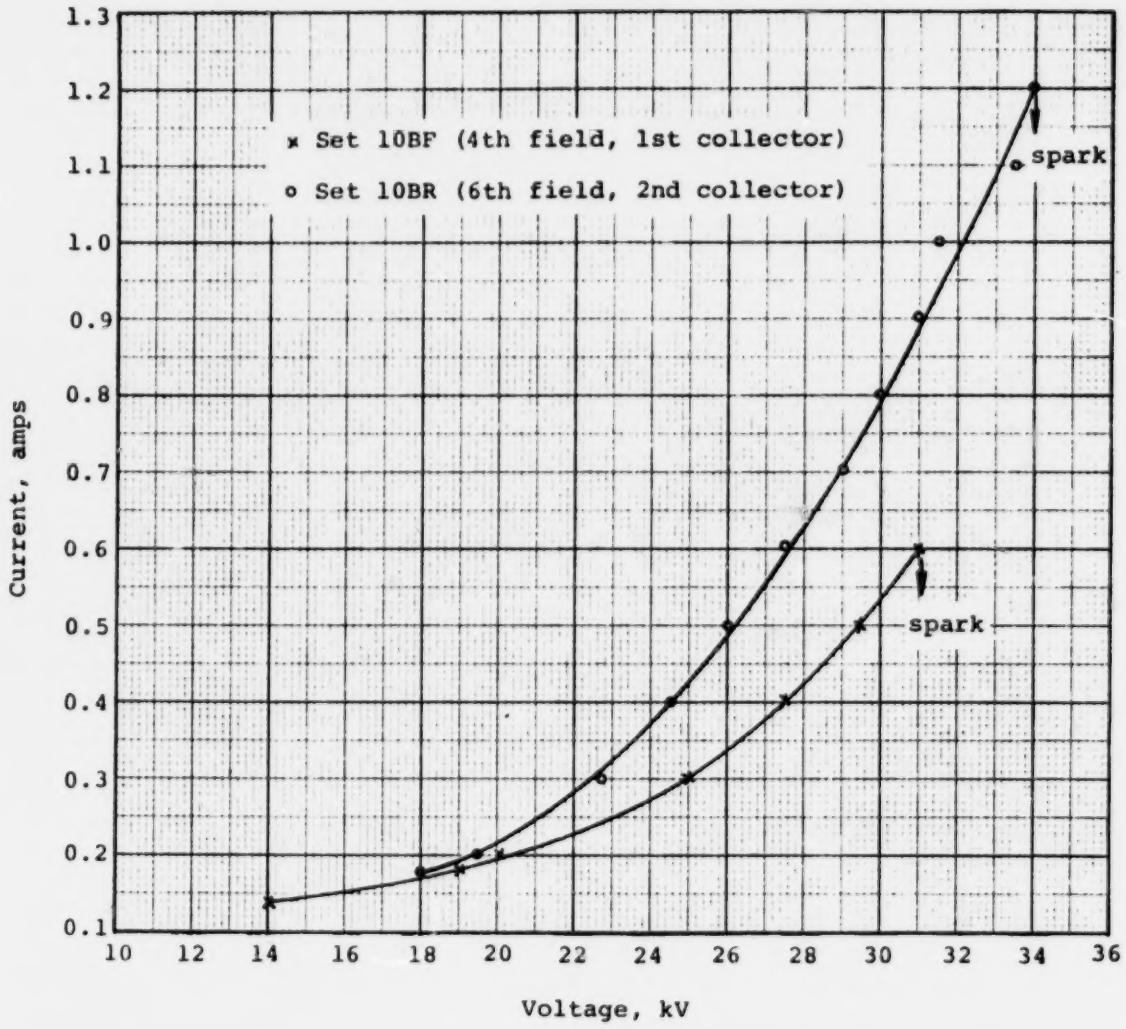


Figure 3-7. Voltage-Current Relationships Obtained on Precipitator "B".

SECTION IV
PERFORMANCE TESTS AT A HOT SIDE ELECTRIC UTILITY BURNING WESTERN COAL

INTRODUCTION

The performance of an electrostatic precipitator was evaluated during April and May 1974. This test is the first detailed analysis of the performance of a precipitator located on the hot gas side of the air preheater (hot side) that Southern Research has conducted. This installation was selected as being representative of a reasonably well designed hot side precipitator collecting fly ash that resulted from the combustion of the class of coals designated as low sulfur western coals.

In general, the testing procedures described in Section II of this report were followed. However, some discrepancies in the test results were observed. The first discrepancy that was noted was the difference in the volume flow rates as measured at the inlet and outlet sampling points of the electrostatic precipitator. There was a consistent reduction in the gas volume sampled at the outlet of the device as compared to the inlet by approximately twenty percent. At the time of testing these differences were noted and the measurement equipment checked. No obvious problems were noted in the test equipment or procedures.

At the conclusion of the tests, this problem was discussed with a power company engineer. He pointed out that a fire in the air preheater required a modification to the air preheater such that the pressure drop downstream from the test precipitator was significantly greater than that in the adjacent unit. Since the two units were not physically separated by a partition, the excess gas in the inlet was traversing the demarcation line between the units and passing through the adjacent air heater. This fact was not known during the test program.

The total mass loadings as determined by the mass trains differ from that determined by the impactors for the initial tests. The inlet mass loadings differed by as much as a factor of six. An attempted analysis of this discrepancy led to a retest to evaluate the causes of this variation. Southern Research funded a second trip to the power station to investigate these interferences. The results of these tests are discussed later in the section describing substrate interference.

Another problem was noted in the analyses of the test results. The volume flow rates were essentially the same for both the 220 and 260 MW loads, even though the boiler generation rates were varied. This is probably because the fans were operated on manual control rather than on automatic. The boiler master (boiler automatic control system) was "hunting" at the reduced load conditions resulting in about a 10% swing in the fan flow. This instability caused a severe problem in maintaining isokinetic flow with the sampling equipment. Therefore, on test three the boiler was switched to manual control with the operator maintaining the fixed flow rate. This manual control method was utilized for the remainder of the tests.

There is also reasonable doubt that the operator changed the fan settings for the 260 megawatt tests. If this is correct, then this provides an explanation for the near constant volume flow rate that was experienced throughout the test period.

ELECTROSTATIC PRECIPITATOR DESCRIPTION

The electrostatic precipitator installed at the hot side installation consists of four individual precipitators of two sections, each section consisting of 13,582 m^2 of plate area collecting particulate from a gas stream of about 1.33×10^4 m^3/min of gas at a nominal temperature of 371°C at full load conditions (generation rage of 357 megawatts).

The tests were conducted on one of the four sections (the right half) at less than full load, with volume flow rates on the order of 9628 m^3/min. This corresponds to a specific collection electrode area at test conditions of about 1020 m^2 of collection plates per thousand actual cubic meters per minute of gas (310 ft^2/kcfm). The precipitator is equipped with plate spacings of 22.9 cm (9") and 0.28 cm (.109") diameter corona electrodes. The unit consists of 58 gas passages formed by 9.1 m (30 ft) high collection electrode 12.2 m (40 ft) long. The average gas velocity through the precipitator during the tests was 1.16 m/sec (3.8 fps). The precipitator is powered by 8 electrical sets each connected to 1700 m^2 (18,270 ft^2) of collection electrodes.

RESULTS

Mass Loadings

The results of the inlet and outlet mass loadings as determined by Guardian Systems, Inc., are given in Table 4-1 A and B.

Fractional Efficiency Measurements

Data for the determination of fractional efficiencies of the hot side precipitator were obtained by three measurement techniques.

TABLE 4-1A
EPA METHOD 5 INLET MASS CONCENTRATION TESTS.
APRIL-MAY 1974

Run No.	1	2	3	4	5	6	7
Date	4/29	4/30	4/30	5/1	5/2	5/2	5/3
Time	15:45	15:00	20:00	10:25	10:00	13:33	08:00
Duration (minutes)	90	150	90	258	108	96	240
Moisture content %	6.0	9.8	5.0*	8.5	7.9	8.7	8.1
Gas Temperature °C	309	314	311	320	284	305	305
Gas Velocity ft/min	2431	925*	4353*	2489	2241	2547	1796
Gas Velocity m/sec	12.4	4.7*	22.1*	12.6*	11.4	13.0	9.1
Sample Vol. DSCF	33.51	21.14	53.87	100.91	36.42	37.87	68.33
Sample Vol. DSCM	.95	0.6	1.53	2.86	1.03	1.07	1.93
Mass Concentr. Gr/ACF	3.69	8.15	2.10	3.85	3.94	3.02	1.91
Mass Concentr Gm/AM^3	8.44	18.65	4.80	8.81	9.01	6.91	4.37

*Suspect test error

TABLE 4-1B
EPA METHOD 5 OUTLET MASS EMISSION TESTS
APRIL - MAY 1974

Run No.	1	2	3	4	5	6	7
Date	4/29	4/30	4/30	5/1	5/2	5/2	5/3
Time	16:10	15:04	20:03	10:19	10:00	13:40	08:07
Duration (minutes)	150	123	120	300	108	108	240
Moisture Content %	5.6	8.4	9.2	8.7	9.0	8.4	8.3
Avg. Temp. °C	304	305	311	290	283	302	291
Gas Velocity FPM	1618	1516	1627	1530	1698	1809	1450
Gas Velocity M/sec.	8.22	7.7	8.3	7.8	8.6	9.2	7.4
Sample Vol. DSCF	34.14	93.01	96.01	229.21	87.50	92.05	176.03
	.97	2.63	2.72	6.49	2.48	2.61	4.98
Mass Conc. Gr/ACF	.055	.022	.0244	.0115	.0167	.017	.0127
Gm/AM^3	.13	.05	.06	.03	.04	.04	.03
Vol Flo. ACFM	318005	297960*	319700	300710	333728	355544	285000
M^3/Sec	150	141	151	142	158	168	135
Specific Collection Area $ft^3/KCFM$ $m^2/m^3/sec$	460 90.5	490 96.4	457 89.9	486.5 95.8	438 86.2	411 80.9	513 101
Generation Rate Mw	220	220	220	220	260	260	260
Efficiency %	98.5	99.73	98.84	99.70	99.58	99.44	99.11

*Vol. flo corrected from inlet

Inertially determined size/mass concentration data were obtained using modified Brink Cascade impactors for inlet sampling and Andersen Mark III Cascade impactors for outlet sampling. Glass fiber impaction substrates were used in both cases and all impactor samples were obtained in-situ. The impactors provided size information over the range from about 0.3 μm to 10 μm. A total of 14 inlet samples at six sampling points were obtained over the four-day period from April 29 through May 2. A total of 9 outlet samples at 6 sampling points were obtained of which 3 were lost due to handling errors while transporting. Figures 4-1 and 4-2 show the results of the inlet and outlet samples in the form of cumulative mass loading (grains/dscf) plotted against particle diameter. The indicated diameters were based on a particle density of 2.27 grams/cm^3. The vertical bars represent ± 1 standard deviation ranges of the cumulative loadings.

The total mass loadings as indicated by the impactors differed from that indicated by the Method 5 mass train. Table 4-2 shows the average mass loading as determined by each method.

TABLE 4-2

MASS CONCENTRATIONS AT INLET AND OUTLET OF PRECIPITATOR AS MEASURED BY TWO METHODS. DRY GAS AT STANDARD CONDITION.

	Method 5 Loading	Impactor Loading
Precipitator Inlet	17.8 gm/m^3 σ = 9.65	12 gm/m^3 σ = 4
Precipitator Outlet	.13 gm/m^3 σ = .07	.023 gm/m^3 σ = .011

This significant difference in loadings point to the possibility of reactions between the gas stream and the sampling equipment. There is the possibility of a material loss from the substrates of the impactor as well as a possible reaction with the mass train probe or filter media. The difference may also be related to the fact that no complete traverse was made with the impactors.

Optically determined size/concentration data over a size range from about 0.3 to 2.0 μm diameter were obtained using Climet and Royco particle counters at the inlet on April 29 and 30 and at the outlet using only the Royco particle counter on May 1, 2, and 3. Size/concentration data were obtained by diffusional methods using diffusion batteries and condensation nuclei counters simultaneously with the optical data. A dynamic sedimentation method was used

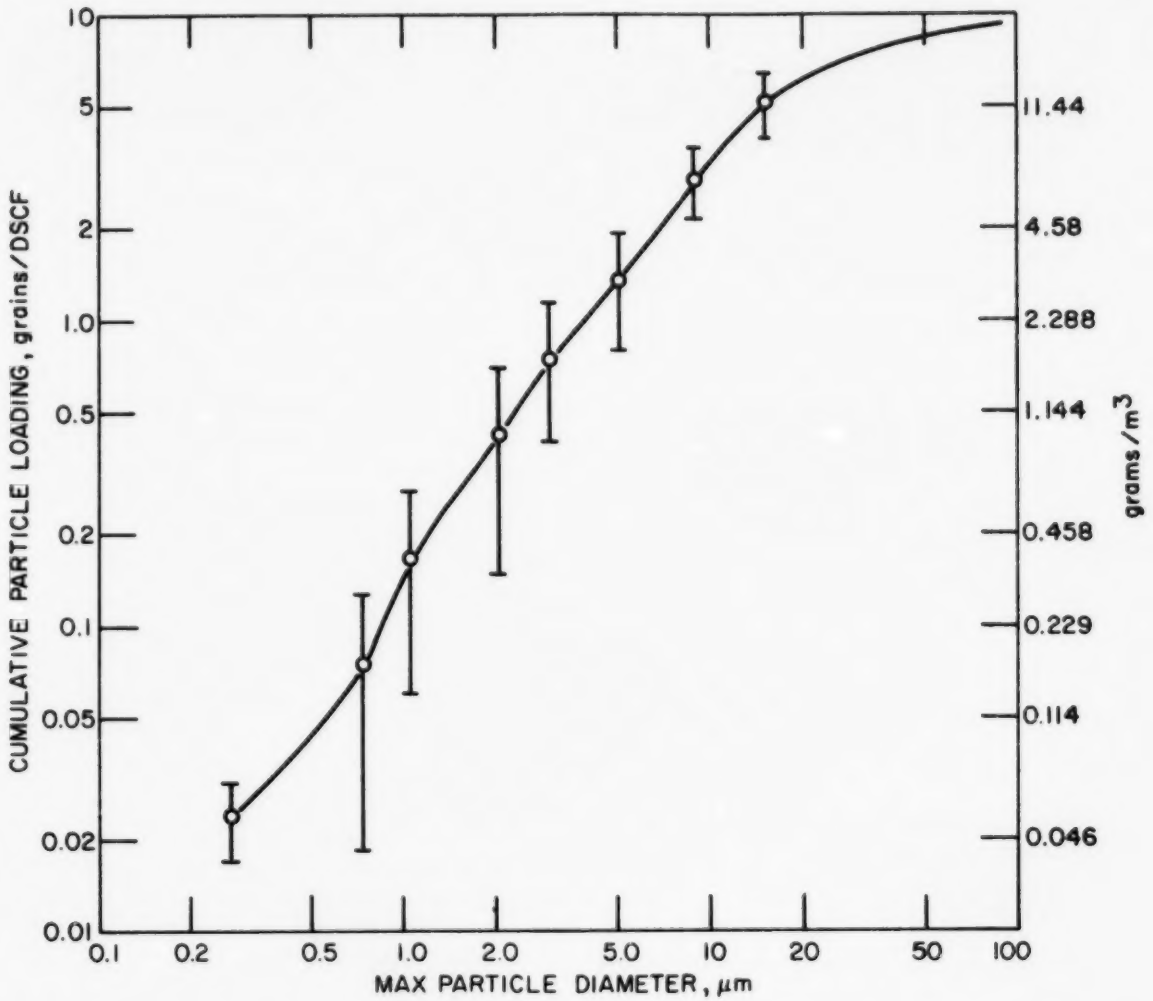


Figure 4-1. Cumulative Particle Size Distribution of the Inlet Particulate.

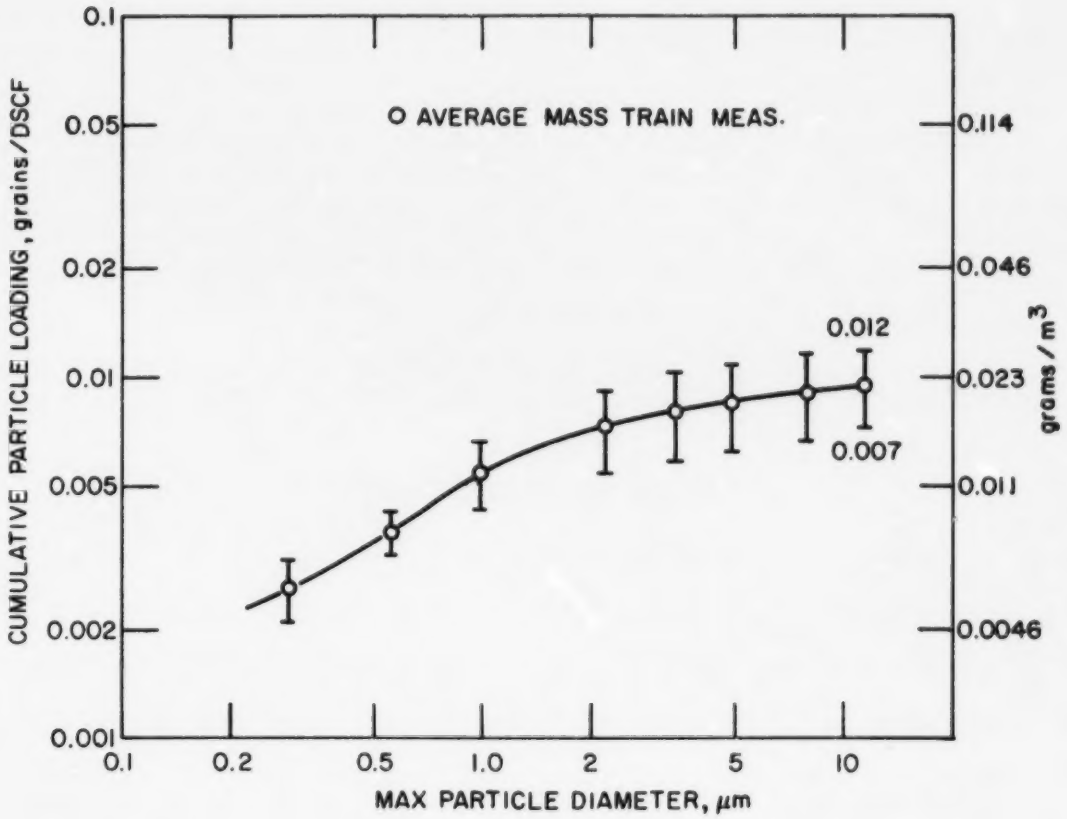


Figure 4-2. Cumulative Outlet Particle Size Distribution.

to correlate the optical diameter with the inertial behavior of the particles (i.e., Stoke's diameters). The optical and diffusional data represent single point samples at both the inlet and outlet of the precipitator. Extractive sampling and extensive dilution at the sample gas stream was required in obtaining the optical and diffusional data. Figure 4-3 shows the results of the measurements. The data in Figure 4-3 are presented in terms of cumulative concentration by number density (#/cm^3) of particles having diameters larger than or equal to the indicated diameters.

Figure 4-4 shows the fractional efficiencies of the precipitator as calculated from these data.

Laboratory Particulate Resistivity

The laboratory resistivity was determined for samples one and two that represented the extremes in sodium oxide concentration. The results of these tests are shown in Figure 4-5. The difference in resistivity at temperatures greater than 300°F are as expected for the observed variation in chemical composition.

Coal Analyses and Chemical Analyses

Coal samples were analyzed for each test during the series. The proximate analysis for each sample is given in Table 4-3.

TABLE 4-3

PROXIMATE COAL ANALYSIS

Item	Test 1	2	3	4	5	6
Moisture %	4.8	4.3	4.3	4.1	3.9	4.2
Ash %	22.4	24.7	24.5	24.36	23.3	23.45
Sulfur %	0.85	1.07	1.02	0.87	1.13	
Heating value (thou Btu/lb)	9.9	10.1	9.8	9.7	10.0	9.98

The coal was considered to be essentially constant during this test program. The coal samples were taken downstream from the pulverizer. Thus the moisture content may be low and the other values correspondingly high in comparison to raw coal samples.

Fly Ash Chemical Analysis

Fly ash samples were collected during the test program for laboratory analysis. The results of these determinations are given in Table 4-4.

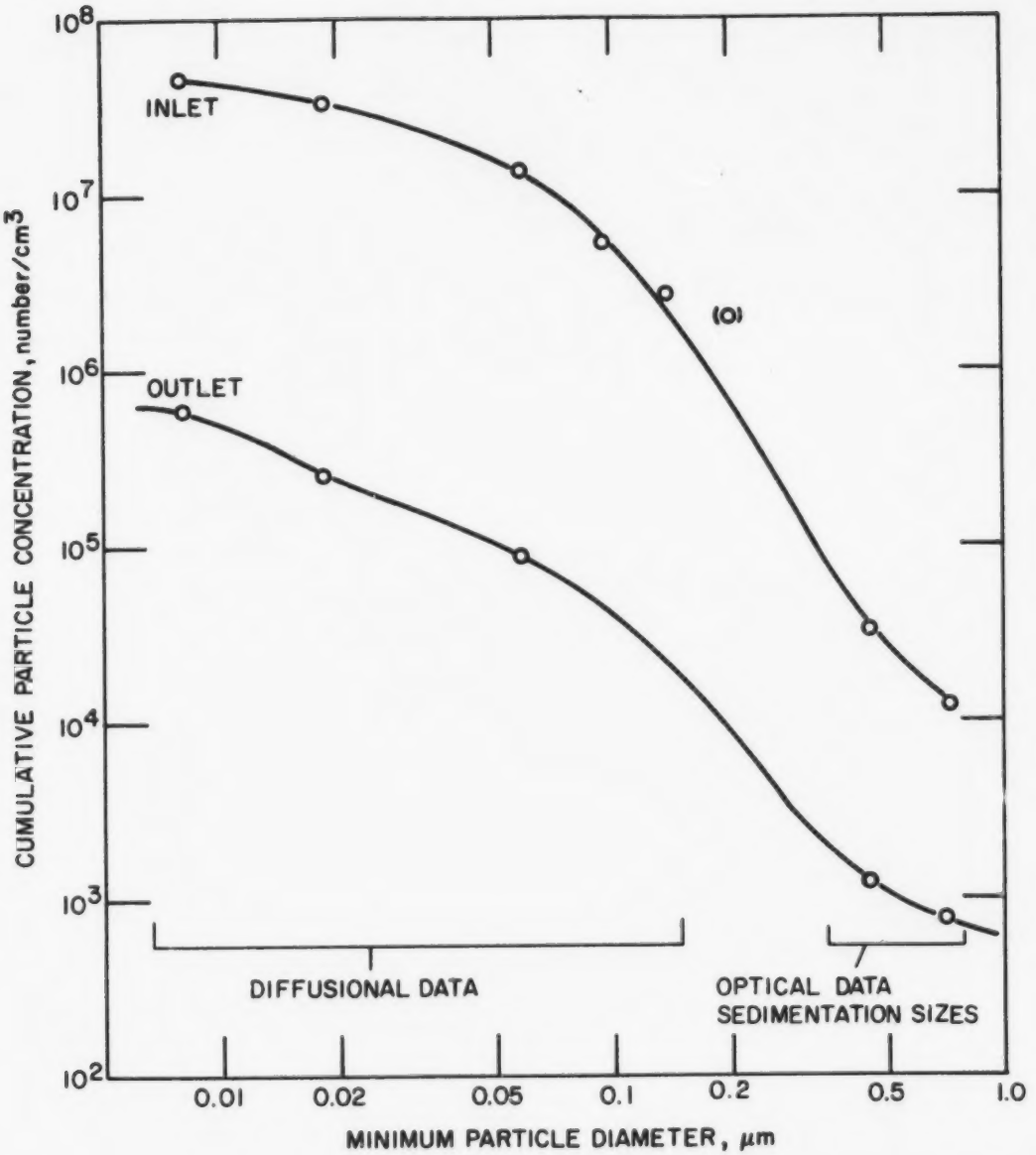


Figure 4-3. Cumulative Particle Number Concentration

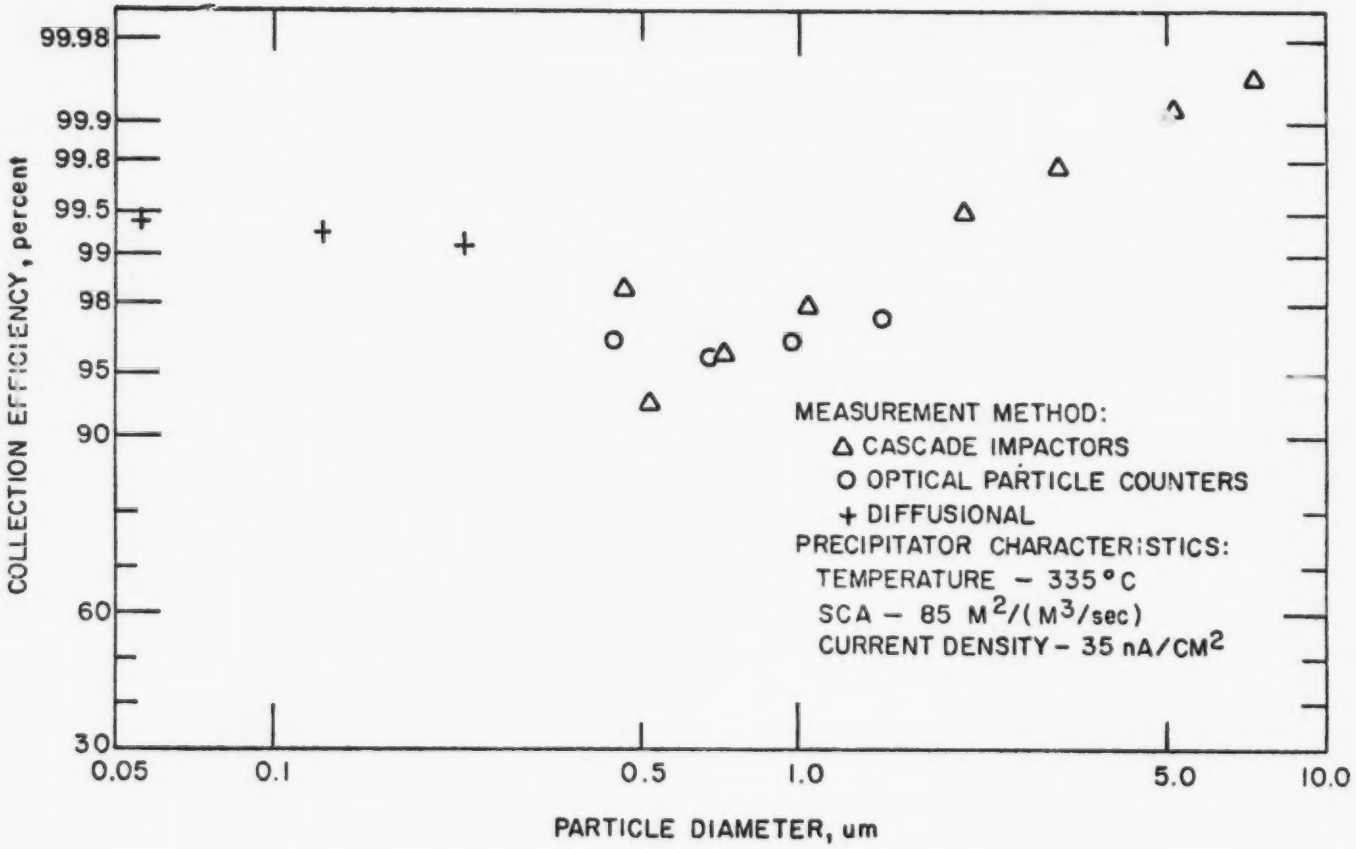


Figure 4-4. Measured fractional efficiencies for the hot side electrostatic precipitator with the operating parameters as indicated, installed on a pulverized coal boiler.

TABLE 4-4

CHEMICAL ANALYSIS FOR FLY ASH

	1	2	3	4	5
Li_2O	.02	.02	.02	.02	.02
Na_2O	1.36	1.45	1.40	1.45	1.59
K_2O	1.18	1.19	1.19	1.23	1.37
MgO	1.06	1.03	.97	1.03	.93
CaO	4.98	4.90	4.91	5.00	4.56
Fe_2O_3	3.78	3.82	3.71	3.52	3.41
Al_2O_3	27.16	26.85	26.96	26.90	26.90
SiO_2	57.27	57.29	57.25	57.25	57.42
TiO_2	1.05	1.11	1.05	1.05	1.11
P_2O_5	.17	.18	.16	.16	.18
SO_3	.75	.38	.41	.40	.69
LOI	.60	.60	.61	.50	.66

Electrical Conditions

The precipitator power supply secondary voltage and current were monitored during the test program. The readings are given in Table 4-5. The power supply readings were reasonably consistent during the test period. The precipitator layout and pertinent information are shown in Figure 4-6. The current density was consistently lower on the left side inlet (section A) for each test. This could in part be due to some electrode misalignment for this field.

SRI-Sponsored Mass Train and Impactor Measurements

Background -

A discrepancy was noted between the mass loadings as given by the EPA Method 5 technique and the impactors. The data obtained from the mass tests at this plant indicated that the Andersen impactors from a single point sampling location gave only about 20% of the total outlet grain loading as obtained with an EPA Method 5 sampling train. During December 1974, similar tests (also reported in this document) were conducted at Citadel Cement Co. in North Birmingham, also considered to be a hot precipitator 260°C(500°F). Again a significant discrepancy between loadings were shown. While at Citadel a comparison of the mass train measurements and Andersen measurements was planned. A Gelman 47 mm filter was run ahead of an Andersen impactor and one Andersen impactor was run ahead of a mass train. The Andersen impactor was run ahead of the mass train in an attempt to determine if there were appreciable differences between a traverse and a single point measurement; due to the size of the Andersen impactor, a traverse of only one-half the area of the stack was possible. The cause of the discrepancies between the loadings as indicated by the two instruments required further investigation.

Test Plan -

A test program was devised with the objective of determining the cause or causes for the anomalies between the two systems with respect to mass train grain loading vs impactor grain loading measurements.

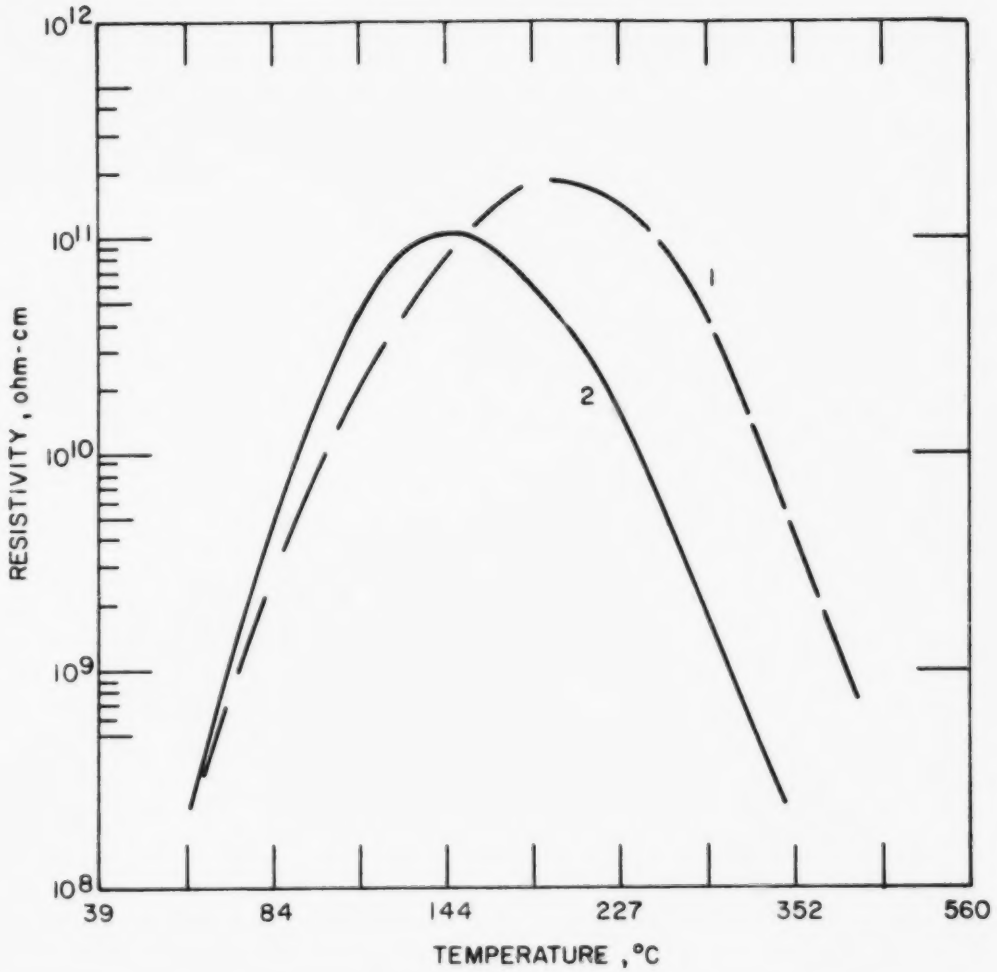
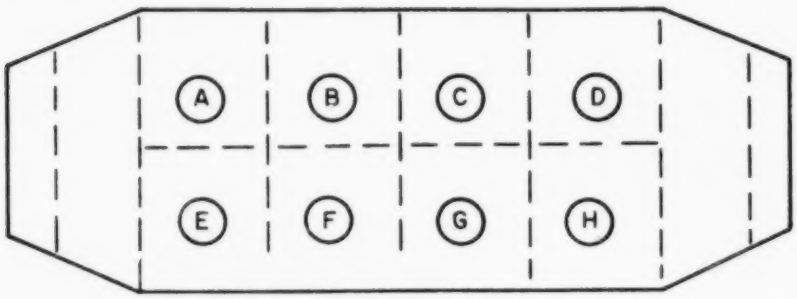


Figure 4-5. Laboratory resistivity as a function of temperature for fly ash. Moisture content maintained at 9.5% by volume. Sample 1 was from April 29 and Sample 2 from April 30, 1974. (Heating Cycle)

TABLE 4-5
Power Supply Readings

	A		B		C		D		E		F		G		H	
	Voltage (kV)	Current (ma)	Voltage (kV)	Current (ma)	Voltage (kV)	Current (ma)	Voltage (kV)	Current (ma)	Voltage (kV)	Current (ma)	Voltage (kV)	Current (ma)	Voltage (kV)	Current (ma)	Voltage (kV)	Current (ma)
April 29, 1974	36.3	485	29.2	700	22.0	675	20.0	755	21.5	900	19.0	925	16.3	995	15.5	922.5
April 30, 1974	37.5	523	31.9	650	24.3	686	21.0	737	20.4	936	17.4	936	16.4	989	16.3	927
May 1, 1974	37.4	634	32.2	684	25.4	702	22.8	706	21.0	940	19.0	936	17.0	994	17.0	932
May 2, 1974	36.3	550	32.6	635	24.9	688	20.5	708	23.0	915	20.0	940	17.7	948	16.7	910
May 3, 1974	36.2	550	31.4	680	24.2	702	21.8	722	22.0	920	19.2	910	16.7	994	16.8	920
Average	36.8	548.4	31.5	670.0	24.2	690.6	21.2	725.6	21.6	922.2	18.9	929.4	16.6	984.0	16.5	922.3
Average Current Density, nA/cm^2		32		39.4		40		42.7		54.2		54.7		57.9		54.3

Note: Each power set is connected to 1.7×10^7 cm^2 (18270 ft^2)



Inlet Duct 24'-11" x 5'-3" Outlet Duct 29' x 5'-3"

Total Area 146,160 ft^2 = 13,579 m^2

Plate Spacing 9" = 23 cm

Corona Wire Dia. 0.1055 - .27 cm

4 Pptrs Total Installed

Area for each power supply $1.7x10^3$ m^2= 18,270 ft^2

Guar. 99.5 @ 350 MW

Test 1. Vol flow - 24 11/12' x 5.25' x 2431 ft/min = 318,005 = 8600 m^3/min

SCA = 146,160 : 318,005 = 459 ft^2/kcfm = 90.35 m^2-sec/m^3

Current Density = 42 $\mu A/ft^2$ = 43 nA/cm^2

Avg. Eff. 7 tests 3.085 inlet, .0228 outlet = 99.26

Figure 4-6. Precipitator Information and Layout for the Collector.

The test as conducted consisted of: Andersen impactors run as they have been in the past, single point. These tests are labeled as A-0, 1, 2, or 3. -0 indicates the blank run which consisted of a Gelman 47mm filter preceding the impactor. -1, 2 or 3 indicate run number. The Andersen impactor was run at a single point in front of a mass train. These tests are labeled MT+A-0, 1, 2 or 3; -0 again indicating a blank run, where a Gelman filter preceded the impactor which in turn preceded the mass train. Tests were also conducted using a Gelman 47mm filter as an in-stack filter ahead of the mass train. These tests are labeled MT+G-1, 2, or 3 depending upon the run. There were also single point Brink impactor runs labeled as B-1. All tests were run at single points, but not for the same duration due to boiler problems.

Results -

The results obtained from these tests are tabulated in Tables 4-6, 4-7, and 4-8. Table 4-6 consists of operating conditions from day to day plus weight catches obtained for each test. Table 4-7 consists of a summary of the data in gm/m^3(dry) for each filtering device. Table 4-8 tabulates the stage weights for each impactor run and Table 4-9 is a table for the previous data obtained in the Spring of 1974.

Conclusions -

The data from Table 4-6 indicates that the impactors on the blank runs, when preceded by a Gelman filter, gained 56 mg each, although sampled volumes differed from 1.065 to 0.215 m^3. This resulted in 0.053 and 0.260 grams/m^3 due to apparent gas phase interferences. If this interference were consistent from run to run the stage weight gains could be subtracted from the weight gains during normal runs and a particle size distribution could be plotted. But run #A-3 shows that the weight gain of the impactor is less than that of the blank runs. Note that A-3 has a sampled volume of 0.435 m^3 and a weight gain of only 50.52 mg (0.116 gram/m^3). This test indicates non-reproducible interference in the Andersen impactors.

Test MT+A-0 and MT-1, where both tests were run at the same point on the same day, show identical grain loadings when comparing the Gelman prefilter to the mass train, 0.023 and 0.022 grams/m^3. However, due to operator error, the isokinetic variation was high on run MT+A-0. Also for test MT+G-2 and MT-2, the Gelman prefilter shows fair agreement with the mass train, 0.014 vs 0.021 grams/m^3. Probe washes for tests MT+A-1 and MT+G-1 appeared to be contaminated with some type of hydrocarbon, even though they were downstream from the impactor and Gelman filter. Test MT-3

TABLE 4-6

POWER STATION TEST DATA
1/20-75 to 1/24/75

Date	Test No.	Point Loc.	Probe Length	Mega Watts	Barometric Pressure in Hg	Stack Pressure in Hg	Stack Temp °C	Meter Temp °C	Volume Sampled by ft³	Volume Sampled dscf	Velocity at Point fps	Time Sampled min	Sample Nozzle	% Moist.	Weight Gains, Mg: Gelman	Impactor	Probe Wash	MT Filter	Total Weight Gain	% Iso-Kinetic
1/21	MT+A-0	6-1	3'	331	24.4	24.9	330	15	35.025	37.674	40	90	4mm	7.3	24.42	56.34	5.4	-1.55	84.61	463
1/21	A-0	2-3		331	24.4	24.9	330	-6	8.413	7.574	40	90	4m		8.22	56.66			64.88	100
1/21	A-1	5-1		331	24.4	24.9	344	-4	21.495	19.098	40	240	4mm			108.64			108.64	93
1/21	MT+A-1	7-1	3'	331	24.4	24.9	344	10	89.112	75.776	40	240	.25"	8.4		115.16	113.9	2.22	231.28	120
1/21	MT+G-1	9-1	10'	331	24.4	24.9	344	10	98.153	83.267	42	240	.25"	8.4	12.72		186.1	214.5	411.32	126
1/21	MT-1	6-1	old 5'	331	24.4	24.9	344	10	94.255	80.008	40	240	.25"	8.4			33.5	15.32	48.82	127
1/22	B-1	3-3		213	24.9	25.3	300	-2	10.31	9.336		119	4mm	4.8		33.76			33.76	120
1/22	A-2	4-3		213	24.9	25.3	300	-2	10.466	9.477		112	4mm	3.8		72.02			72.02	117
1/22	MT+A-2	5-3	new 5'	213	24.9	25.3	300	19	38.567	32.412	26	157	.25"	8.1		67.66	4.7	2.19	74.55	108
1/22	MT+G-2	7-2	3'	213	24.9	25.3	300	17	47.631	40.231	23	136.48	.25"	8.1	15.76		15.9	1.66	33.32	178
1/22	MT-2	9-3	old 5'	213	24.9	25.3	300	18	27.694	23.305	26	105	.25"	8.2			4.1	9.89	13.99	118
1/23	A-3	4-2		263	24.7	25.0	315	-8	16.739	15.351	33	70	.25"	7.2		50.52				88
1/23	MT+A-3	9-3	new 5'	263	24.7	25.0	315	19	36.240	30.209	35	100	.25"	6.4		62.68	3.9	-0-	66.58	120
1/23	MT+G-3	5-2	3'	263	24.7	25.0	315	16	40.361	33.957	36	106	.25"	6.9	13.2		31.0	4.6	48.8	127
1/23	MT-3	7-3	old 5'	263	24.7	25.0	315	14	34.588	29.32	36	95	.25"	2.9			79.4	1.0	80.4	117

Table 4-7
Summary,
Test Data

Date	Test No.	Port-Point Location	Load MW	gm/M³ (dry) Gelman	Impactor Prefilter	Impactor	Impactor Back Filter	Mass Train	Total
1/21	MT+A-0	6-1	331	.023	.008	.039	.006	.004	.079[1]
1/21	A-0	5-3	331	.038	.022	.212	.030		.302
1/21	A-1	5-1	331			.182	.019		.201
1/21	MT+A-1	7-1	331			.049	.005	.054	.108[3]
1/21	MT+G-1	9-1	331	.005				.169	.174[2]
1/21	MT-1	6-1	331					.022	.022
1/22	B-1	3-3	213			.097	.031		.128
1/22	A-2	4-3	213			.241	.027		.268
1/22	MT+A-2	5-3	213			.066	.008	.008	.081
1/22	MT+G-2	7-2	213	.014				.015	.029
1/22	MT-2	9-3	213					.021	.021
1/23	A-3	4-2	263			.103	.013		.116
1/23	MT+A-3	9-3	263			.066	.007	.005	.078
1/23	MT+G-3	5-2	263	.014				.037	.051[3]
1/23	MT-3	7-3	263					.097	.097[3,4]

[1]Impactor loose after test, nozzle was not pointed into gas stream when removed from port. May have happened when removing probe from port.

[2]May have had leak in probe, probe heater failure -- 8' of 10' probe at subfreezing temperature. Probe wash discolored, appeared to contain oil.

[3]Probe wash appeared to contain oil.

[4]Possible contaminant, from varnish or top of sample container, in probe wash.

TABLE 4-8

IMPACTOR STAGE WEIGHTS
(milligrams)

	A-0 1/21/75	MT+A-0 1/21/75	A-1 1/21/75	MT+A-1 1/21/75	B-1 1/22/75	A-2 1/22/75	MT+A-2 1/22/75	A-3 1/23/75	MT+A-3 1/23/75
Gelman	8.22	24.42							
SO	4.72	8.34			6.58				
S1	4.98	5.30	29.92	24.00	7.80	5.80	7.80	6.60	6.78
S2	4.96	5.22	12.42	13.52	9.10	25.38	6.72	5.50	6.42
S3	5.58	5.40	10.12	13.06	2.06	5.60	6.68	5.58	6.12
S4	5.76	4.80	9.54	11.28		4.96	7.18	5.08	6.38
S5	6.06	5.44	9.26	12.06		5.58	8.16	5.52	8.38
S6	6.10	5.24	8.78	12.86		5.64	9.24	6.08	10.02
S7	5.94	5.50	9.40	10.00		6.34	8.14	5.92	7.32
S8	6.04	4.86	9.02	8.32		5.52	6.42	4.80	5.18
SF	6.52	6.24	10.18	10.06	8.22	7.20	7.32	5.44	6.08
Σ Impactor Mass	56.66	56.34	108.64	115.16	33.76	72.02	67.66	50.52	62.68
Impactor Loadings gm/m^3	.2647	.0528	.2008	.0537	.1279	.2687	.0737	.1161	.0733
Sample Time (min)	90	90	240	240	119	112	157	70	100
Vol Sampled dscf	7.574	37.674	19.098	75.776	9.336	9.477	32.412	15.351	30.209
Vol Sampled m^3	.214	1.067	.541	2.1416	.264	.268	.918	.435	.855

TABLE 4-9
OPERATING AND TEST DATA
GENERATING STATION
4/29/74 to 5/3/74

Date	Test No.	Load MW	SCA ft^2 1000 cfm	Eff.	Stack Temp °C	Vol. at Meter Cond. m^3	Meter Temp °C	Meter Pressure in Hg	Stack Pressure in Hg	Weight Gains, mg			gm/m^3 dry dscf
										Probe Wash	Filter	Total	
4/29	1	220	460	98.5	305	1.20	32	24.98	25.26	287.6	11.6	229.2	.249
4/30	2	220	490	99.7	306	3.27	30	24.8	25.26	307.8	27.3	335.1	.103
4/30	3	220	457	99.8	311	3.29	22	24.76	25.26	366.6	26.4	393.0	.119
5/1	4	220	486	99.7	291	8.31	38	24.68	25.16	353.6	71.4	425.0	.050
5/2	5	260	438	99.6	283	3.24	28	24.68	25.16	201.6	31.5	233.1	.071
5/2	6	260	411	99.4	303	3.39	41	24.51	25.05	230.9	31.0	261.9	.076
5/3	7	260	513	99.1	291	9.47	35	24.81	25.25	269.6	89.5	359.1	.037

may have had the probe wash contaminated from the varnish on the lid of the sample container since virtually all of the mass was obtained from the probe wash. Test MT+G-1 may have a low Gelman filter weight due to a probable leak in the sampling probe. Such a leak could also have contributed to the anomalously high mass found in the probe and filter. Another consideration is the probable failure of the probe heater during this run. The probe was exposed to sub-freezing temperatures over a length of approximately 2.5 meters. Such exposure without proper heating could have caused condensation of what appeared to be high molecular weight hydrocarbons found in the probe wash.

Previous mass train traverses from last Spring's (1975) test gave about 0.096 gm/m^3 at a pressure of 1 atmosphere and a temperature of 20°C. Single-point impactor data, which apparently were obtained in the absence of significant weight gains from gas phase interference, gave about 20% of the particulate mass (0.019 gm/m^3) obtained with the mass train traverse. The previous Andersen single point measurements are in qualitative agreement with the single point measurements obtained with the Gelman and mass train runs of January 1975.

SECTION V
CITADEL CEMENT, BIRMINGHAM, ALABAMA

INTRODUCTION

A test program was conducted at the Citadel Cement Company in Birmingham, Alabama, to evaluate an electrostatic precipitator collecting the particulate emissions from a wet process cement kiln. This installation represents a well designed electrostatic precipitator for the cement industry.

The cement kiln generates particulate in two ways: (1) combustion products and (2) the abrasive action of the rotating kiln. A mixture of lime, sand, rock wool with about 25% by weight of water are introduced into the three rotary kilns. The heated process air and combustion products flow countercurrent to the process materials into the electrostatic precipitator.

ELECTROSTATIC PRECIPITATOR DESCRIPTION

The precipitator installed at Citadel Cement Company consists of two separate units, each unit consists of 4 fields in series with the gas flow and 32 gas passages which are 22.86 cm (9 in.) wide. Each field is 2.7813 m (9'-1½") deep and 10.9728 m (36') high. The combined units have an effective plate area of 15,625 m^2 (168,192 ft^2) and handle about 130.04 m^3/sec (275,500 cfm) at ∿296°C (565°F), which gives a specific collecting area of 120.2 $m^2/(m^3/sec)$ (610 ft^2/1000 cfm). The precipitator has a total of 8 TR sets. The discharge electrodes consist of barbed wires with the barbs being approximately 12.7 cm (5") apart. The precipitator is equipped with vibrating rappers on the collecting plates and discharge electrodes.

RESULTS

The results of the field measurements are given below.

Mass Loadings

The mass loading measurements are summarized in Table 5-1. The E.P.A. Method 5 was utilized for the mass measurement. As the table indicates, inlet mass loadings were not obtained with the mass train during the test series. However, inlet mass train measurements from a previous test series conducted by Guardian Systems were made available to Southern Research Institute and were used in calculating the estimated collection efficiencies.

TABLE 5-1

CITADEL CEMENT OUTLET MASS

TEST RESULTS

Run Number	1	2	3	4 [1,2]	5 [1]
Date	12/17	12/18	12/19	12/20	12/20
Time Of Day	1310	920	1047	1015	1015
% Moisture	23.76	24.7	25.31	23.57	20.07
Velocity, m/sec	15.58	15.58	15.11	17.17	16.73
Volumetric Flow m^3/sec	125.35	125.39	121.55	138.14	134.59
Volumetric Flow DSm^3/sec	50.36	50.48	47.55	53.67	55.06
Concentration mg/m^3	9.156	9.156	11.445	15.336	4.578
Concentration mg/DSm^3	22.890	25.179	29.757	38.913	13.734
Percent Isokinetic	90.4	90.4	93.3	92.8	103.3
Estimated Collection[3] Efficiency, %	99.84	99.84	99.80	-	99.92

1 Traverse was only 50% of stack area
2 Mass train preceded by Andersen impactor, impactor catch = 54mg, mass train catch = 27.6mg. Possible leak in probe connection.
3 Based on an average inlet grain loading of $5653.856mg/m^3$ (2.47 gr/acf) obtained during a test series conducted prior to the test series described in this report.

Particle Size Measurements

The test program at Citadel was designed to evaluate a potential interference in the mass and size measurements with regard to either a weight gain or loss with the substrate materials. A variety of sampling procedures were selected and a schedule of the runs are shown in Table 5-2.

The inlet size distribution data were obtained with a modified Brink impactor preceded by a precollector cyclone. The average cumulative mass vs the average particle diameter data from the inlet are shown in Figure 5-1. Andersen impactors were run at the outlet of the precipitator in the stack. Figures 5-2 and 5-3 are average cumulative mass vs average particle diameter plots for the outlet impactor data. Figure 5-2 includes the data obtained on 12/18 and 12/19 whereas the data for Figure 5-3 was obtained on 12/20/74. There was a decrease in the outlet grain loading on 12/20/74 which was reflected in the mass train and impactor measurements. There is no explanation for the decreased outlet loading on 12/20/74. The plant personnel reported that on that particular day, the kilns were more efficient than normal.

Table 5-3 is a comparison of the outlet impactor data and mass train data. Data from run number CC07, where an impactor was run ahead of a mass train, suggests that the substrates were reacting with the gas phase constitutents. This conclusion is based on the results from a chemical analysis of the material found in the probe. The analysis indicated the particulate was similar in composition to the kiln affluent.

Figure 5-4 is a plot of minimum fractional efficiency vs particle diameter. The data used to calculate the fractional efficiencies in Figure 5-4 were not corrected for possible weight gains in the substrate materials, since the weight gain on run number CC09 was less than the weight gain of the impactor in run number CC02 which was preceded by a filter. This indicates that it is not feasible to correct for the substrate interferences with the available data.

Optical and diffusional data were taken at the outlet on the 17th, 18th, and 19th. Only diffusional data were obtained at the inlet on the 20th. No inlet optical data were obtained due to a failure in the Royco optical particle sizing instrument Table 5-4 gives the optical and diffusional data in number/cm^3 for the size indicated.

TABLE 5-2

Schedule of Sampling Runs

Mass Trains #Runs	Impactors #Runs Inlet	Outlet	Date
1	0	2*	12/17
1	2	2**	12/18
1	4	2	12/19
1	4	3***	12/20

* Blank Runs
** Andersen with Gelman Postfilter on one run
*** Andersen preceding mass train on one run

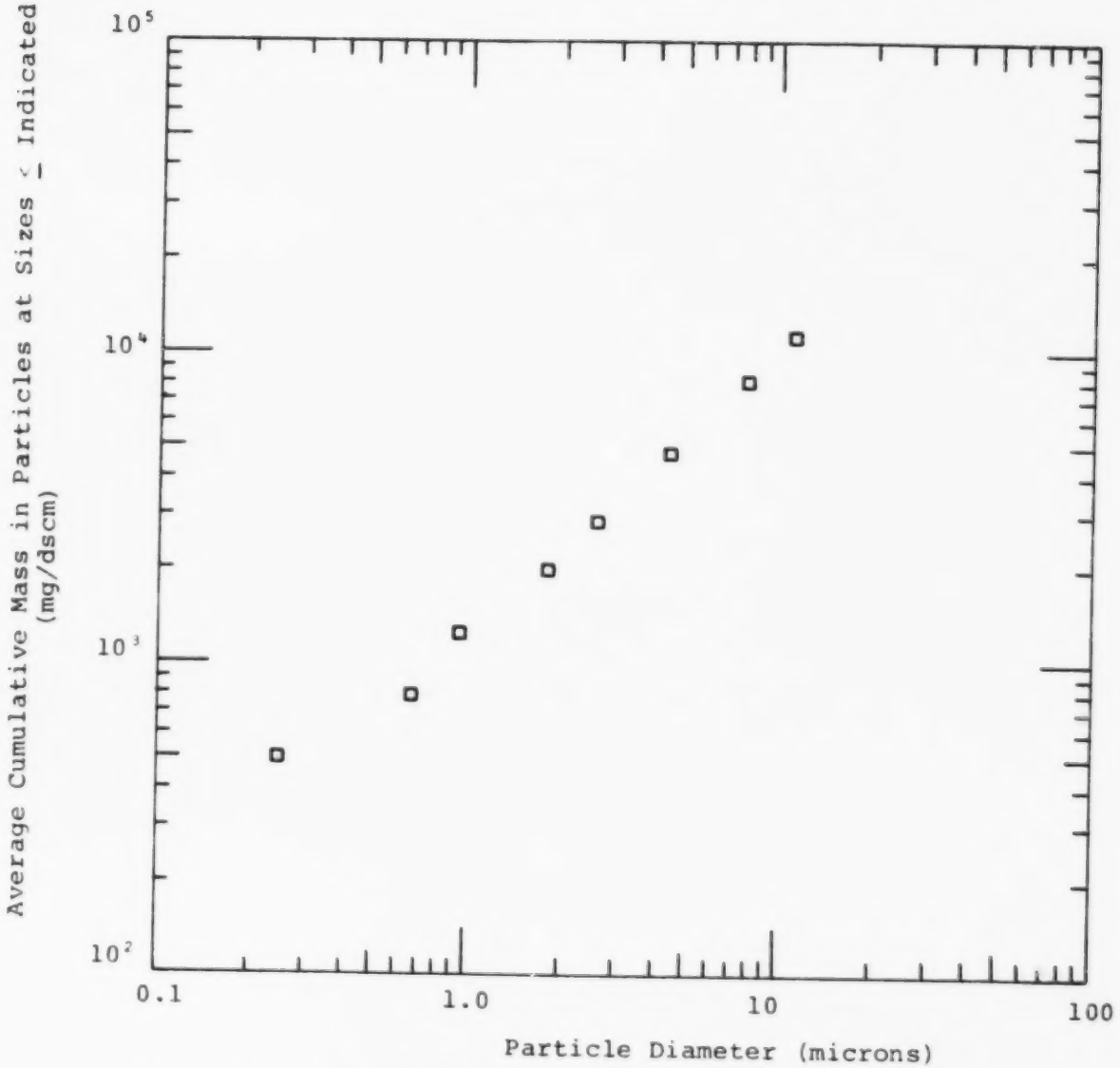


Figure 5-1. Cumulative Inlet Mass Concentration as a Function of Particle Size for the Citadel Cement Installation (average of ten tests).

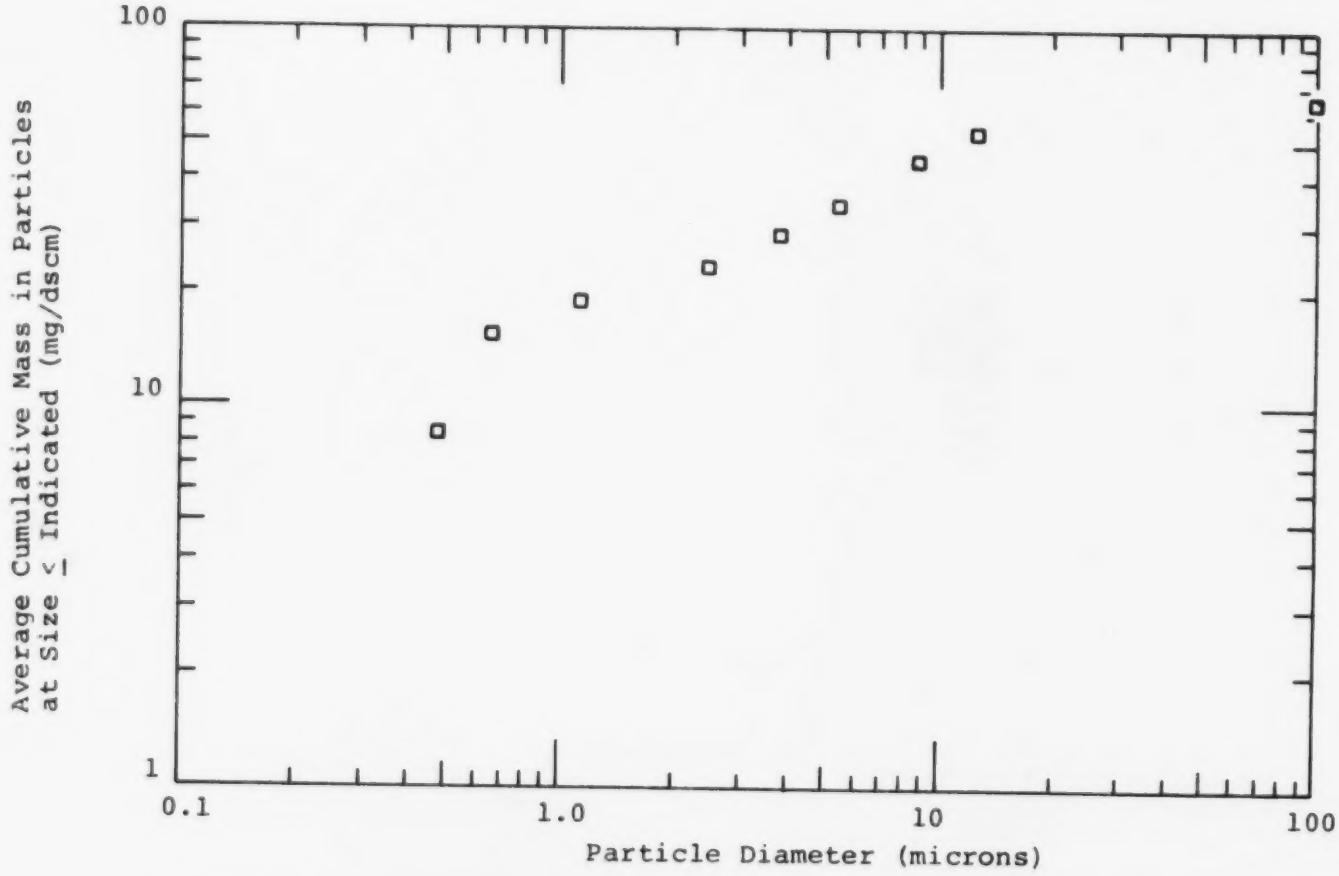


Figure 5-2. Cumulative Mass as a Function of Particle Size from the Outlet of the Citadel Cement Installation - Run 3-6.

TABLE 5-3
OUTLET IMPACTOR/MASS TRAIN COMPARISONS
CITADEL CEMENT

Run No.	Date	Point(1) Location	Stack Temp(°F)	% Moisture	Weight Gains by Location (mg) Nozzle	Prefilter	Impactor	Postfilter	Mass Train Probe	Mass Train Filter	Sampled Gas Volume DSCM	Total(2) Apparent Loading mg/DSCM	Standard(3) Loading mg/DSCM	Secondary(4) Collector Loading mg/DSCM	Run Time Hrs (App)
CC01	12/17/74	S x 2	288	25.35		14.7	27.7				.6312	67.17	23.29	43.88	2
CC02	12/17/74	S	288			7.0	28.7				.5157	69.23	13.57	55.65	2
MT1	12/17/74	T	286	23.76					27.7	3.5	1.4068	22.18	22.18		2
CC03	12/18/74	S	275	21.34	2.2		40.36	1.12			.6663	65.56	63.88	1.68	2
CC04	12/18/74	T	275	22.29	5.0		26.44				.4902	64.14	64.14		2
MT2	12/18/74	T	275	24.70					30.4	4.1	1.4243	24.22	24.22		2
CC05	12/19/74	T	282	26.14	0.7		29.04				.3703	78.61	78.61		2
CC06	12/19/74	S	282	26.40	0.7		21.52				.3061	72.59	72.59		2
MT3	12/19/74	T	282	25.31					33.8	6.0	1.3286	29.96	29.96		2
CC07	12/20/74	T(5)(6)	299	23.57	1.1		53.64		26.2	1.4	2.0813	39.56	26.30	13.26	4
CC08	12/20/74	T	297	24.13	2.1		41.82				1.5158	28.97	28.97		4
CC09	12/20/74	S	297	28.79	1.0		24.74				.7949	32.38	32.38		4
MT4	12/20/74	T(5)	295	20.07					35.5	6.5	3.0226	13.895	13.895		4

(1) S = Single Point, T = Traverse
(2) Total Apparent Loading = $\frac{\text{Total Catch of all Devices}}{\text{Sampled Gas Volume}}$
(3) Standard Loading = $\frac{\text{Total Catch by First Device}}{\text{Sampled Gas Volume}}$
(4) Secondary Collector Loading = $\frac{\text{Total Catch by Secondary Device}}{\text{Sampled Gas Volume}}$
(5) Traverse over only 50% of stack area
(6) Impactor ahead of Mass train

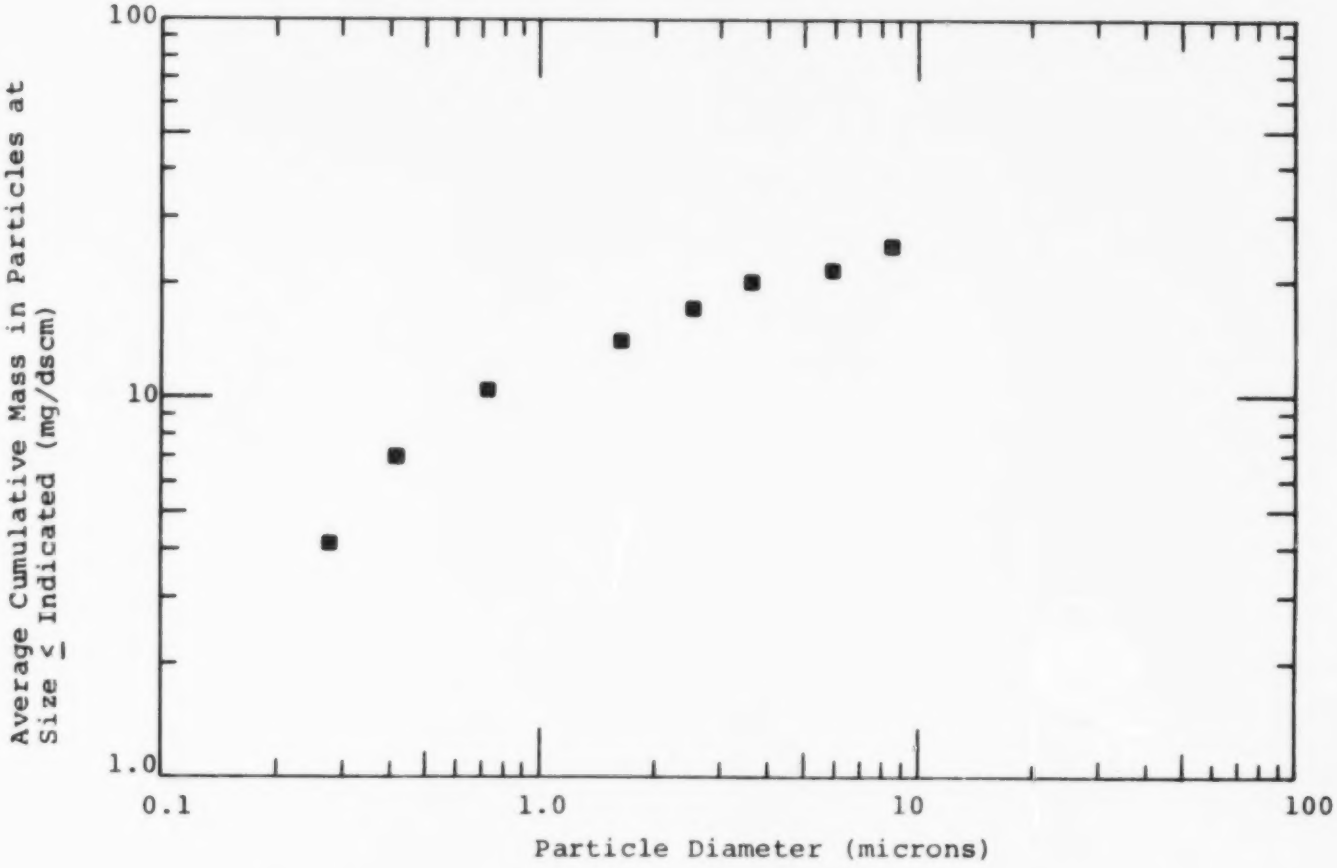


Figure 5-3. Cumulative Mass as a Function of Particle Size from the Outlet of the Citadel Cement Installation - Runs 7-9.

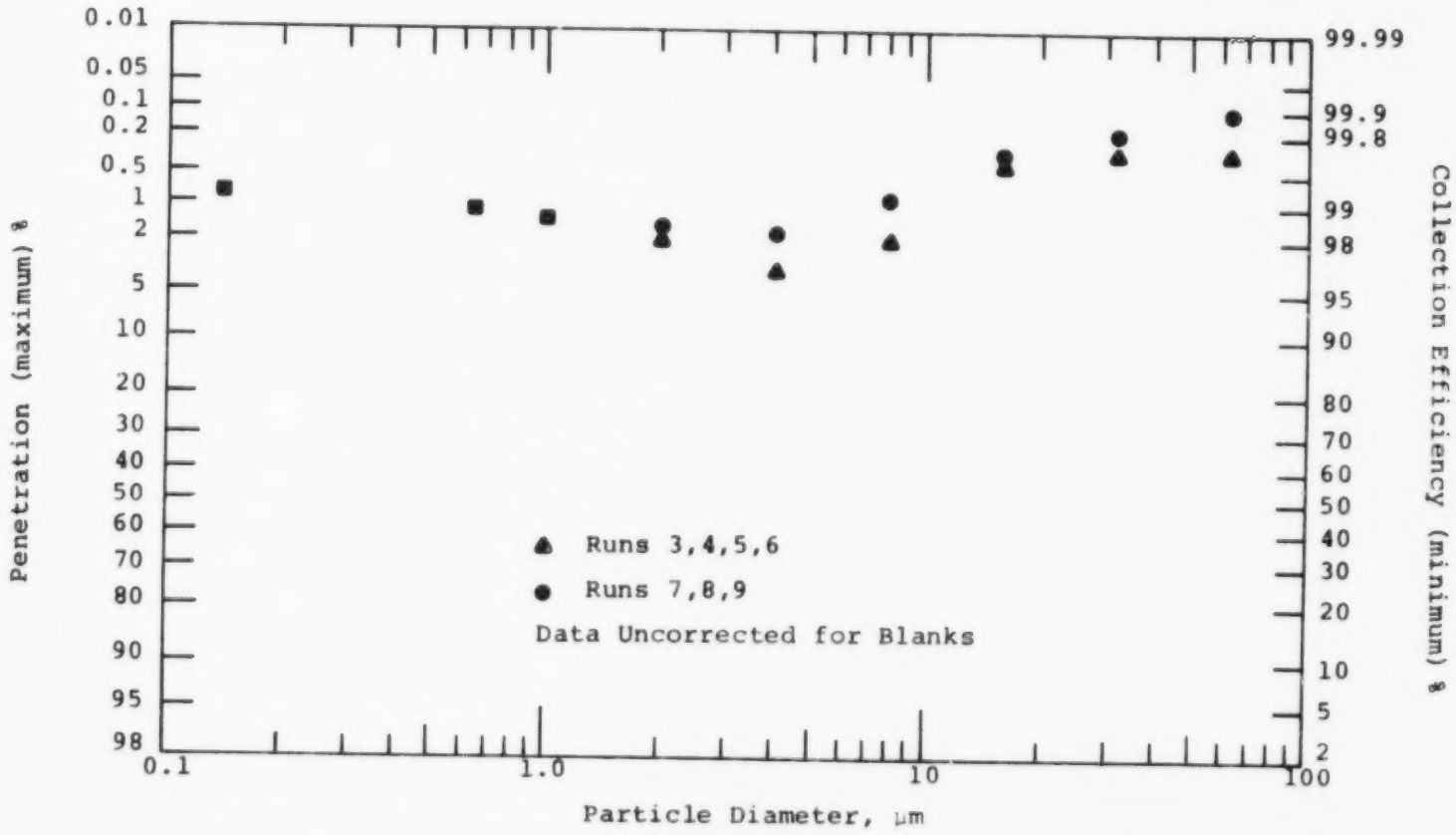


Figure 5-4. Minimum Collection Efficiency as a Function of Particle Size, Citadel Cement Electrostatic Precipitator.

TABLE 5-4

OPTICAL-DIFFUSIONAL DATA

CN Counters & Diffusion Batteries

D_{50} Size µm	Diffusion Battery	Particle Concentration Cumulative Inlet N/cc	Particle Concentration Cumulative Outlet N/cc	Penetration %	Efficiency %
.010	0	1.6×10^6	$<1.2 \times 10^4$	< .75	>99.2
.014	4.4				
.064	5.4	1.07×10^6	$<1.2 \times 10^4$	<1.1	>98.9
.103	2 x 5.4	$.911 \times 10^6$	$<1.2 \times 10^4$	<1.3	>98.7

Royco

D_{50} Size µm	Channel Number	Particle Concentration Cumulative Inlet N/cc	Particle Concentration Cumulative Outlet N/cc
.3	1	-	4.38×10^2
.5	2	-	1.27×10^2
.7	3	-	2.35×10^1
1.3	4	-	7.14×10^0

Electrical Conditions

The secondary current and primary voltage readings were recorded for the precipitator power supplies during the test program. The power supply readings are shown in Table 5-5. The power supplies remained reasonably constant during the test. Figure 5-5 gives a layout of the precipitator and location of the power supplies.

TABLE V-5
POWER SUPPLY READINGS
CITADEL CEMENT COMPANY

	1A		1B		1C		1D		2A		2B		2C		2D	
	Primary Voltage (V)	Secondary Current (MA)	Primary Voltage (V)	Secondary Current (MA)	Primary Voltage (V)	Secondary Current (MA)	Primary Voltage (V)	Secondary Current (MA)	Primary Voltage (V)	Secondary Current (MA)	Primary Voltage (V)	Secondary Current (MA)	Primary Voltage (V)	Secondary Current (MA)	Primary Voltage (V)	Secondary Current (MA)
1974																
12/17	214	-	204	780	171	790	150	1000	230	560	230	710	190	800	145	1000
12/18	193	-	207	780	173	750	150	1000	207	600	218	710	190	800	145	1000
12/19	215	-	200	780	166	740	150	1000	230	600	232	690	200	820	145	1000
12/20	190	-	200	790	173	750	150	1000	230	600	225	690	195	830	145	1000
Average	203	-	202.75	782.5	170.75	757.5	150	1000	224.3	590	226.3	700	193.75	812.5	145	1000
Average Current Density, nA/cm^2		-		40.1		38.8		51.2		30.2		35.8		41.6		51.2

NOTE: Each power set is connected to 1.95×10^7 cm^2 (21,024 ft^2)

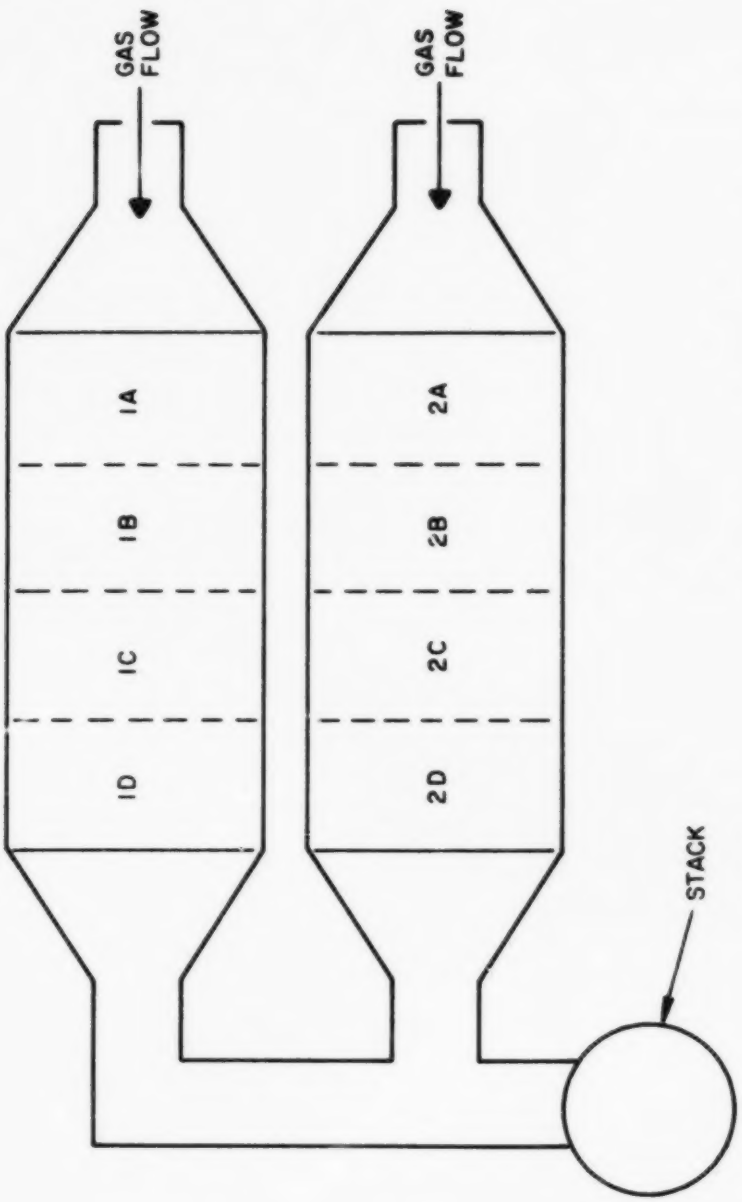


Figure 5-5. Precipitator Layout Citadel Cement.

SECTION VI
COMPARISON OF MEASURED AND THEORETICALLY-PREDICTED COLLECTION EFFICIENCIES

COMPUTER MODEL DESCRIPTION

Southern Research Institute has developed, under EPA sponsorship, a theoretically-based computer model of the electrostatic precipitation process. The model uses the Deutsch equation to predict the collection efficiency of a given size particle in a given electric field at the collecting electrode with a known value of charge in an incremental length section of collection area. Particle charge values as a function of electrical conditions, particle size, and residence time are computed from a theory developed by Smith and McDonald.[1] The electric field at the collecting electrode is computed from voltage-current data using a numerical technique described by Leutert and Bohlen.[2] The collection efficiency of a given size particle over the total precipitator area is determined by summing the collection obtained in each length increment. Polydisperse aerosols are represented by a histogram and overall mass efficiency is obtained by numerical integration over the size distribution.

The following graphs of computed overall mass efficiency as a function of specific collecting area were obtained by using the precipitator geometry, electrical conditions, and the measured inlet size distributions as input data to the computer program for each installation. In addition to the theoretical projections, computed performance relationships are shown for assumed values of gas velocity standard deviation and efficiency losses caused by reentrainment and gas by-passage of the electrified sections. The computer program includes calculation procedures for estimating losses in collection efficiency caused by these non-idealities. The symbol σ_g on the graphs refers to the assumed value of the gas velocity standard deviation, expressed as a fraction of the average velocity. The symbol S refers to the fraction of material assumed to be uncollected per stage due to by-passage (sneakage) and reentrainment, and N designates the number of stages over which the efficiency losses are assumed to occur. A detailed description of the computer model is given elsewhere.[3]

EFFICIENCY COMPARISONS

Figure 6-1 gives the overall mass efficiency obtained at the Gorgas Steam Plant along with the computed performance as a function of specific collecting area. The precipitator was performing reasonably close to the theoretically predicted overall mass efficiency. A σ_g value of 0.25 is considered to represent a

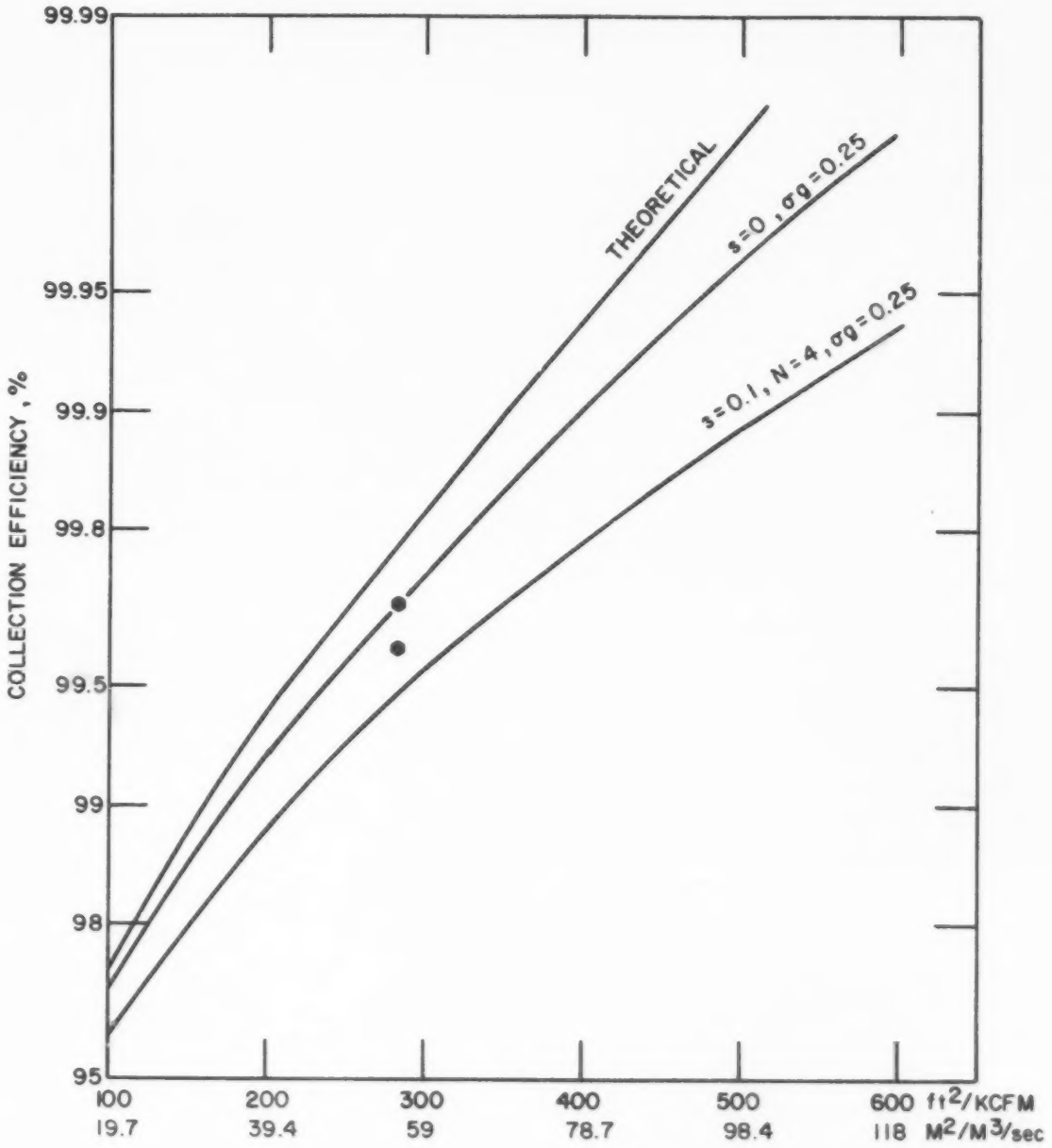


Figure 6-1. Mass Efficiency as a Function of Specific Collection Area at the Gorgas Power Station.

good gas velocity distribution for a full-scale unit. Figure 6-2 shows the average measured and the computed efficiencies as a function of particle size. The line designated S=0, $\sigma_g = 0.25$ indicates the functional form of the correction to the theoretical fractional efficiency predictions which results from using the computer model's procedure for estimating the effects of gas velocity non-uniformity. Note that the computer model appears to underpredict the collection efficiencies of particles smaller than 2.0 μm diameter, and over-predict the collection of larger particles. In view of the difficulties involved in making fractional efficiency measurements and the uncertainties in the theoretical calculations, the agreement between measured and computed results indicated in Figures 6-1 and 6-2 is considered to be reasonable.

Figures 6-3 and 6-4 compare measured and computed performance for the hot side installation. In contrast to the results discussed above, the overall mass efficiency measurements are considerably lower than the theoretical predictions. Possible causes are poor electrode alignment, poor gas velocity distribution, and losses due to sneakage and reentrainment. If a gas velocity standard deviation of 0.25 is assumed, sneakage and reentrainment losses of 10 to 20% over 3 stages are required to reconcile the computed and measured mass efficiency. Whether sneakage and reentrainment are the actual mechanisms by which the losses occurred was not determined. However, the comparatively low slope of the measured efficiency vs particle size data suggests that a major portion of the disagreement is due to poorer-than-predicted large particle collection efficiencies. Reentrainment of particle agglomerates due to rapping would be indicated by this type of disagreement. Note that since the total mass obtained by the outlet impactors was much less than that obtained from the EPA Method 5 train (presumably due to the lack of a complete traverse with the impactors), the true large particle penetrations are probably greater than indicated in Figure 6-4.

Figure 6-5 compares the computed and measured mass efficiencies for the Citadel Cement Kiln. As discussed previously, the "measured" mass efficiencies are based on inlet mass train measurements performed prior to the test series conducted by Southern Research Institute, but the outlet measurements were conducted simultaneously with the impactor measurements. The overall mass efficiency shows reasonable agreement with the theoretical predictions. At the high values of specific collection area encountered during this test series, relatively minor correction factors are required to reduce the computed efficiencies to the measured values. Figure 6-6 compares the theoretical fractional efficiencies with the minimum fractional collection efficiencies obtained from the impactor measurements. As discussed earlier, absolute values of fractional collection efficiency could not be obtained due to substrate interference problems.

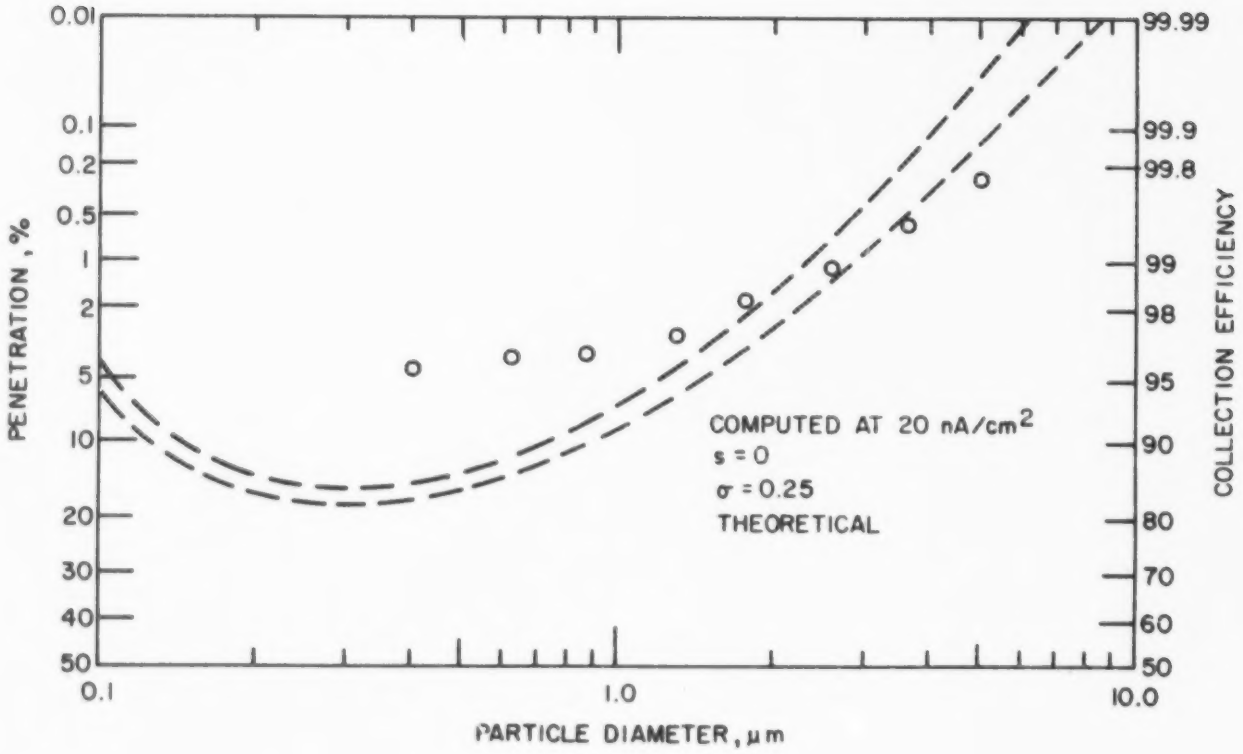


Figure 6-2. Comparison of the Average and Computed Fractional Collection Efficiencies at the Gorgas Power Station.

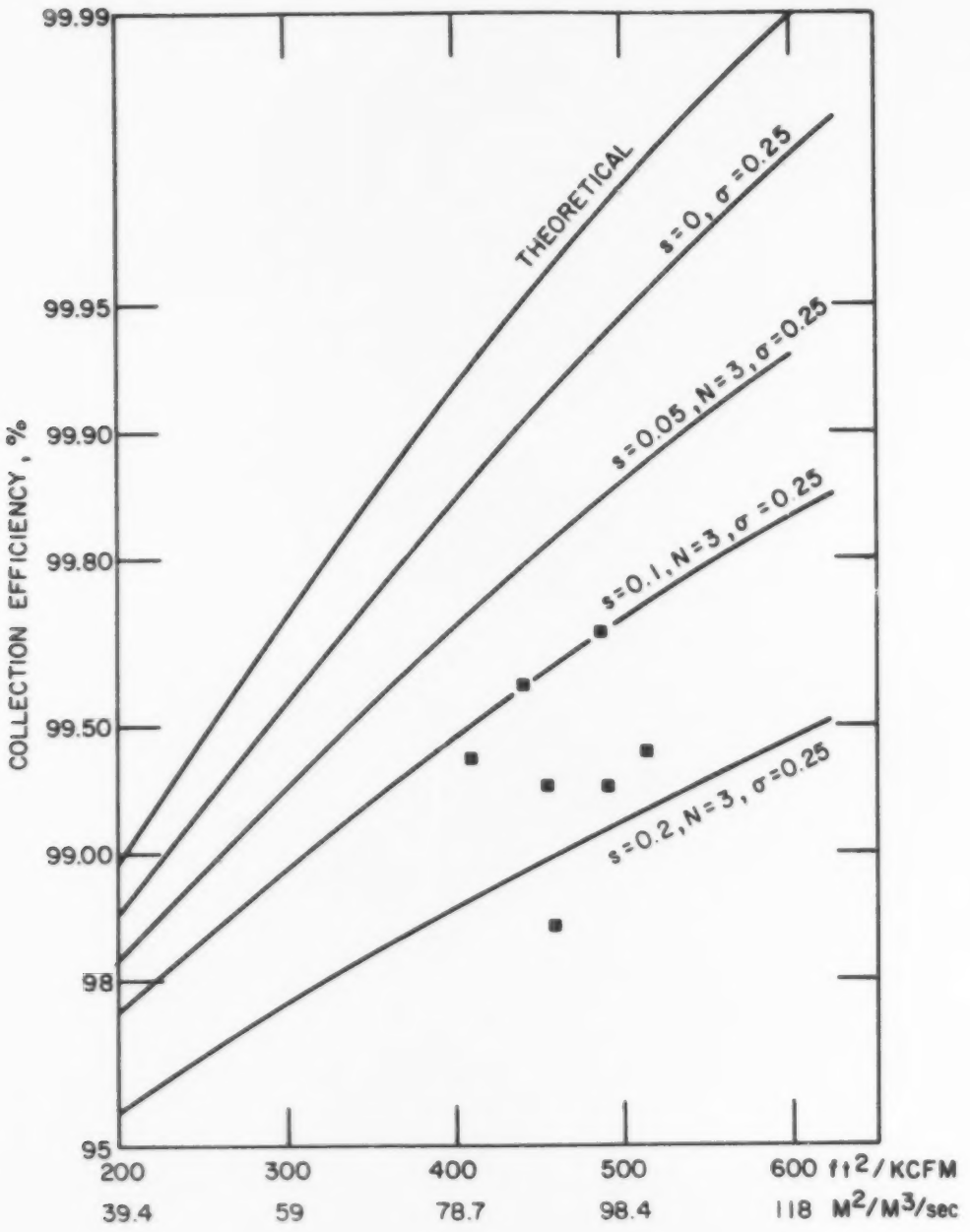


Figure 6-3. Mass Efficiency as a Function of Specific Collection Area at the Hot Side Precipitator Installation.

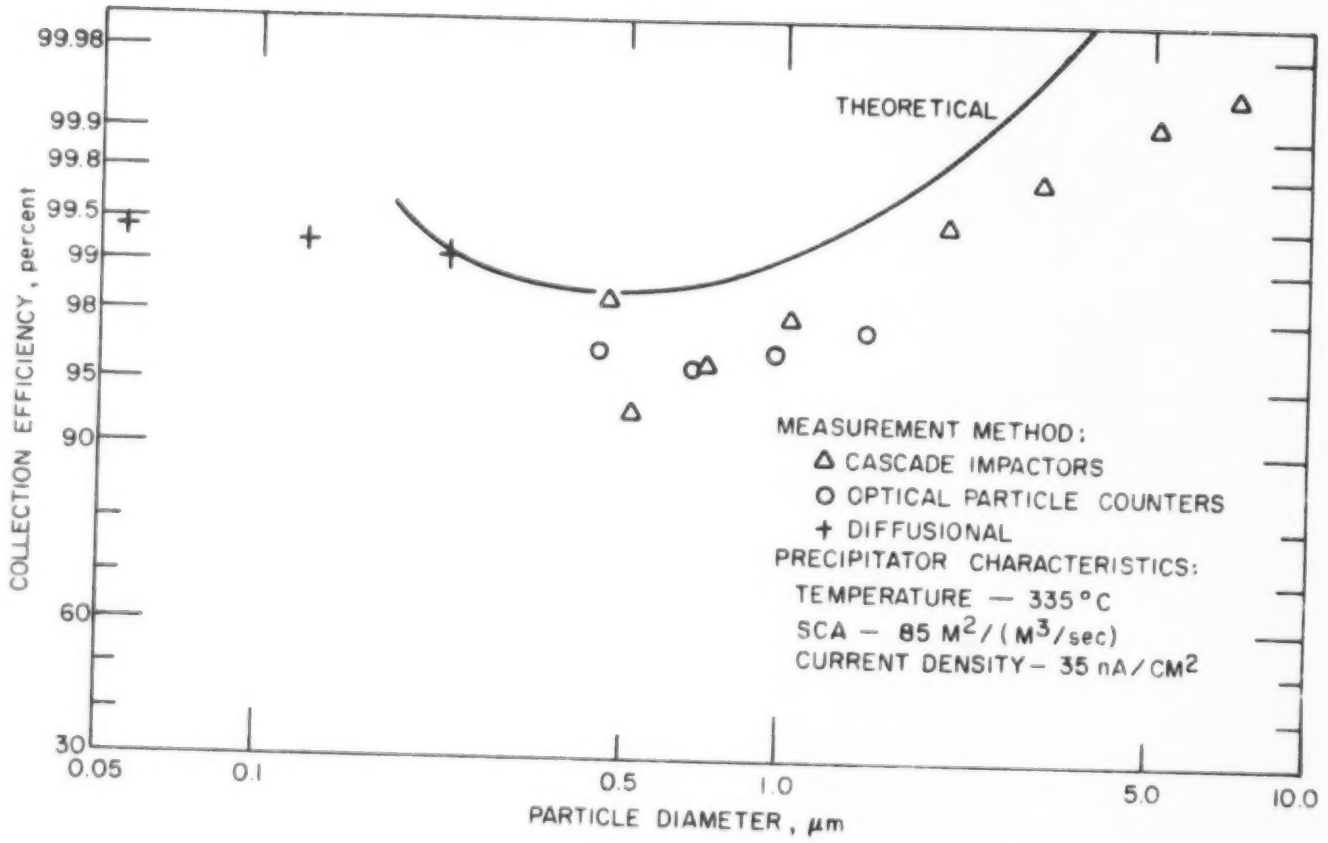


Figure 6-4. Comparison of the Average and Computed Fractional Collection Efficiencies at the Hot Side Installation.

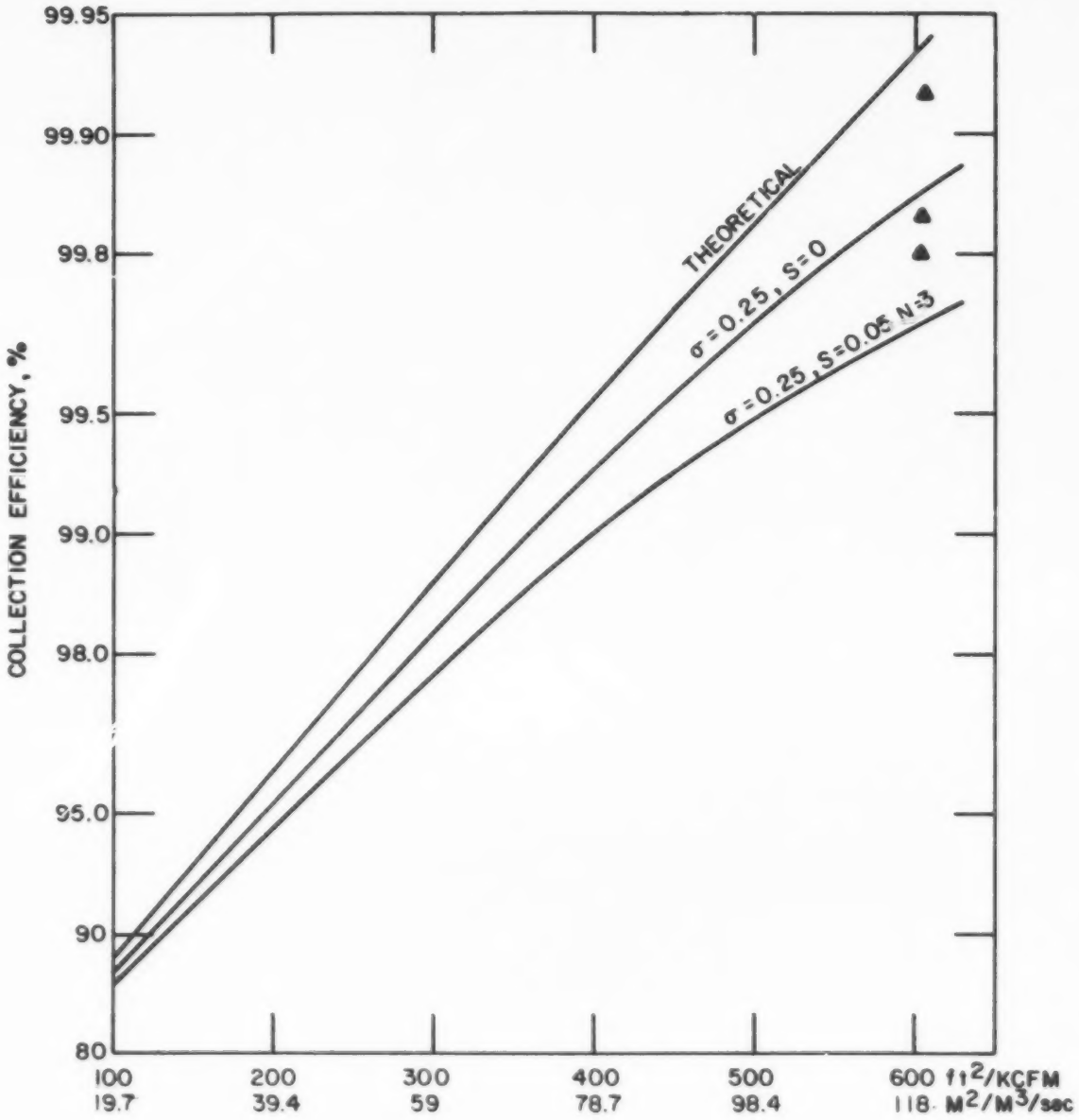


Figure 6-5. Mass Efficiency as a Function of Specific Collection Area at the Citadel Cement Plant.

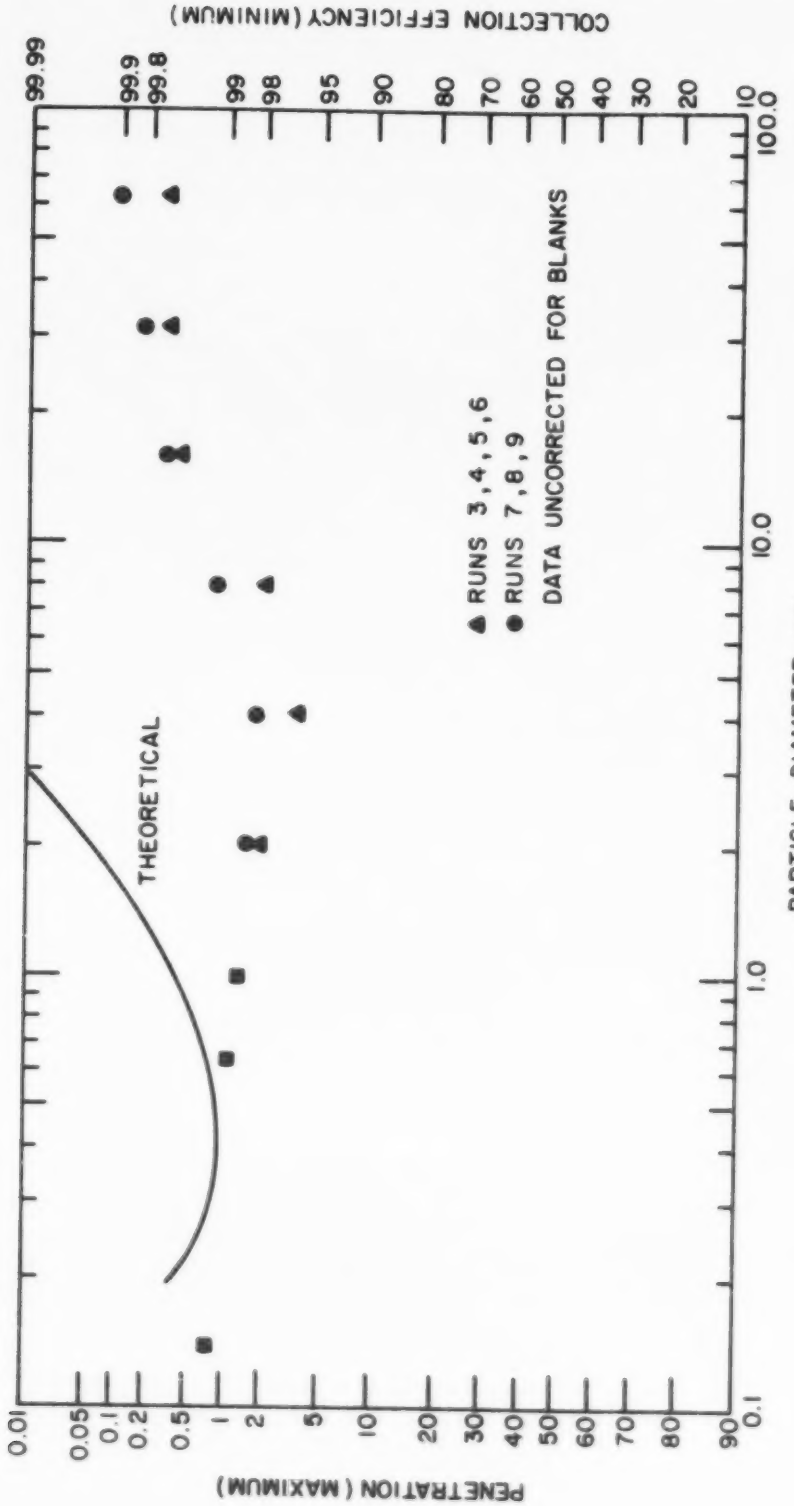


Figure 6-6. Comparison of the Average and Computed Fractional collection Efficiencies at the Citadel Cement Plant.

SECTION VII
IMPACTOR SUBSTRATE AND FILTER MEDIA INTERFERENCE IN A FLUE GAS ENVIRONMENT

During the course of the tests described in this report studies were conducted to evaluate the interference in the determination of particle size distributions by impactors and the mass loadings caused by reactions between the filter media and the flue gas constituents. A variety of substrate and filter media have been tested, both under preconditioned and as delivered conditions. The primary interference phenomenon appeared to be associated with the reaction between the filter media and the sulfur oxides in the flue gas. In each case tested, the filter media contained significant sulfate after exposure to the flue gas environment.

During the time interval between the testing at Gorgas, the hot side installation, and Citadel Cement, other tests were conducted. The filter material was chemically analyzed to evaluate the cause of the weight changes noted.

The results of these studies showed filter substrate gains of as much as 4-5 milligrams when sampling flue gas. These weight gains attributed to gas phase reactions between the sulfur dioxide in the flue gas and sites of high basicity on the filter media, seem to occur at all installations to some degree.

The interferences encountered are illustrated by the results of analyses of the substrate media for the hot side electrostatic precipitator on a coal fired power station, hot side electrostatic precipitator on a cement kiln, and a cold side electrostatic precipitator on a coal fired power station (Bull Run Steam Plant T.V.A. system).

Two series of tests were run at the hot side unit, one in June 1974 and the second during January 1975. In the first series of tests no anomalous weight gains were observed, while blank runs during the second tests showed large weight gains. (It was subsequently learned that Gelman Type A filter material had been changed after the first test series). Filter samples from the second hot side test and the Citadel tests were subjected to several types of analyses, including carbon-hydrogen and soluble sulfate determinations, weight loss at 110° and 600°C, and carbon disulfide extraction followed by gas chromatographic analysis of the extract.

Preliminary data from the hot side filters showed that soluble sulfate levels were significantly higher than obtained from unused filters from the same batch. Soluble sulfate determinations were then made on all of the filters from the two sets showing weight gains. The data in Table 7-1 clearly indicate that sulfate is responsible for the majority of the observed weight gain of each filter.

TABLE 7-1

SOLUBLE SULFATE ANALYSES OF FILTERS
FROM THE HOT SIDE PRECIPITATOR TESTS

Unused samples from batch of first test (6/74). No samples from actual blank run (where no weight gains were observed) are available.

Sample No.	pH[a]	Total mg[b] $SO_4^=$/filter	Reported wt gain, mg
11	6.6	∿0.2	-
18	6.8	∿0.2	-
1F	6.9	∿0.2	
Set 1 from second test (1/75)			
Unused, perforated, unbaked	9.4	∿0.2	-
Unused, perforated, baked	9.4	∿0.2	
S11	7.6	4.4	4.98
S12	7.7	4.2	4.96
S13	7.4	5.1	5.58
S14	7.0	5.0	5.56
S15	7.1	5.6	6.06
S16	7.1	5.6	6.10
S17	7.0	6.0	5.94
S18	6.8	5.6	6.04
Set 2 from second test (1/75)			
Unused, perforated, baked	9.3	∿0.2	-
Unused, solid, baked	9.7	∿0.3	-
S20	6.8	7.3	8.34
S21	6.7	5.1	5.30
S22	7.1	4.6	5.22
S23	7.4	5.2	5.40
S24	7.2	4.5	4.80
S25	7.3	5.0	5.44
S26	7.2	4.6	5.24
S27	7.1	4.9	5.50
S28	7.0	4.6	4.86
S2F	8.2	5.5	6.24

[a] pH determined after the filter sample was in contact with 10 ml of distilled water (pH 5.6) for 1 hr.

[b] The total soluble sulfate was determined by a $Ba(ClO_4)_2$ titration following a water extraction of the sample.

The formation of sulfate is presumed to be due to reaction of SO_2 on basic sites of the filters. Although no filters from the blank run of the initial test were available, unused filters from the same original batch were considerably less basic than unused filters from the second test and, therefore, less likely to cause sulfate formation.

Figure 7-1 shows in graphical form the results from the hot side installation presented in the previous table as well as data from tests at Bull Run Steam Plant. The filter substrate material was the same but the flue gas temperature was quite different (600°F at the hot side unit and 300°F at Bull Run). The solid line indicates a one to one correspondence. No correlation was found between SO_2 content of the gas and weight gains.

Figure 7-2 shows the weight gains of Blank Andersen Impactor substrates versus the temperature of the flue gas. With the exception of the Pre 6/74 point, a linear relationship seems to hold. The Pre 6/74 represents data from the first hot side Steam Plant test shown in Table 7-1. In this case the substrate was quite neutral compared to the basic substrates in the second test.

Figure 7-3 shows the results of tests of several types of 47 mm filter substrate media at different flue gas conditions. The weight gains seem to depend more on the temperature than on the concentration of SO_2 present.

Figure 7-4 shows the results of preconditioning glass fiber substrates. Also even without preconditioning there appears to be a saturation limit at which the weight increases stop.

Figure 7-5 shows the weight gains of Andersen Impactor substrates versus exposure time for preconditioned and unconditioned substrates. The dates at the top of the figure indicate the time at which these substrates were acquired from Andersen 2000, Inc. The 6/74 Normal Substrates show an increase and leveling off with exposure time while the 6/74 Preconditioned Substrates show somewhat smaller weight gain. The "HOT" 6/74 Preconditioned Substrates would seem abnormal compared to Figure 7-2 but apparently the conditioning with hot flue gas reduced the weight gains for this filter set. The 1/75 Normal Substrates show a possible linear relationship, although certainly not conclusively. The Preconditioned 1/75 Substrates indicate a satisfactorily low weight gain versus exposure time.

The general procedure used to obtain samples and investigate this problem in more detail was to pump filtered flue gas through a number of stainless steel 47 mm Gelman filter holders arranged in series. The first filter served to remove the particulate, and the remaining five filters were then only exposed to the gas.

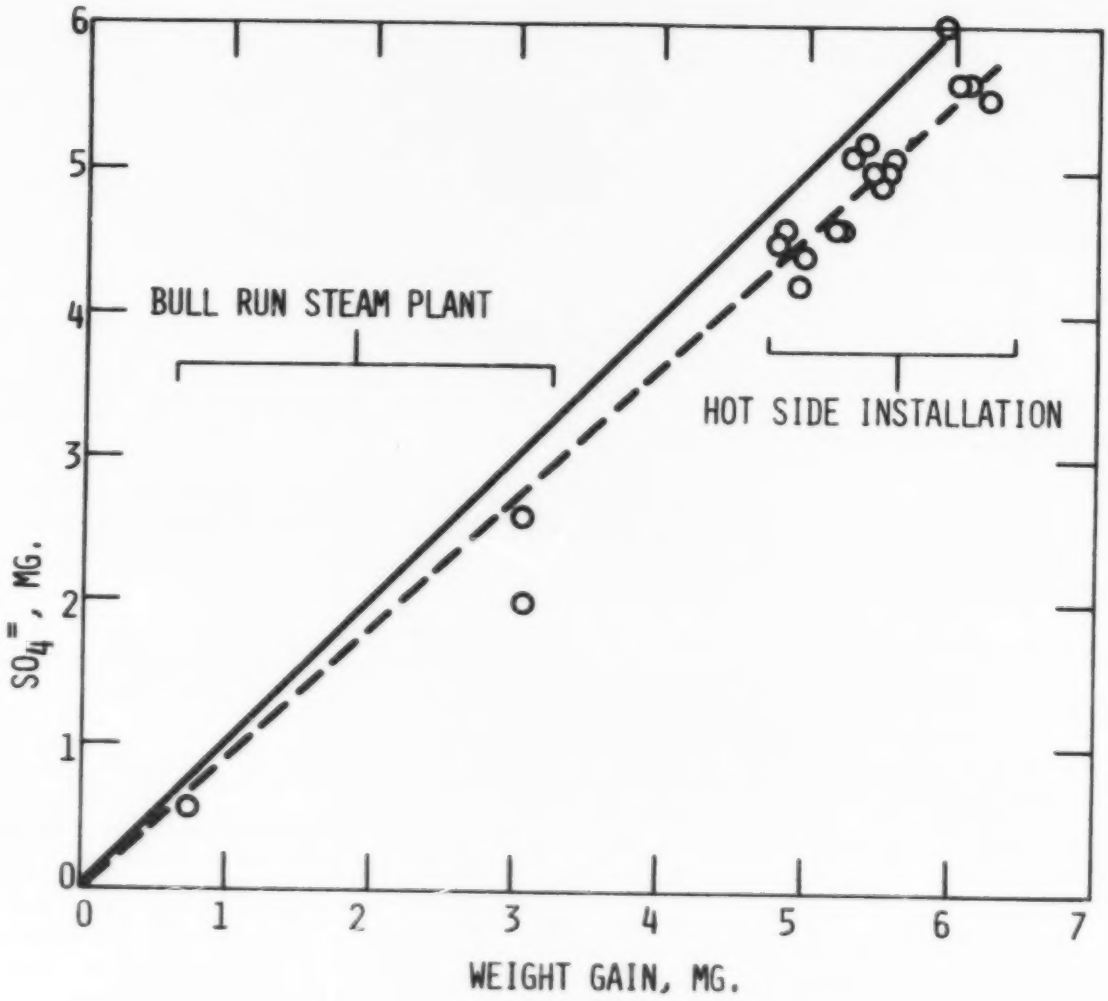


Figure 7-1. Comparison of Weight of Sulfate on Blank Andersen Impactor Substrates and Observed Anomalous Weight Increases.

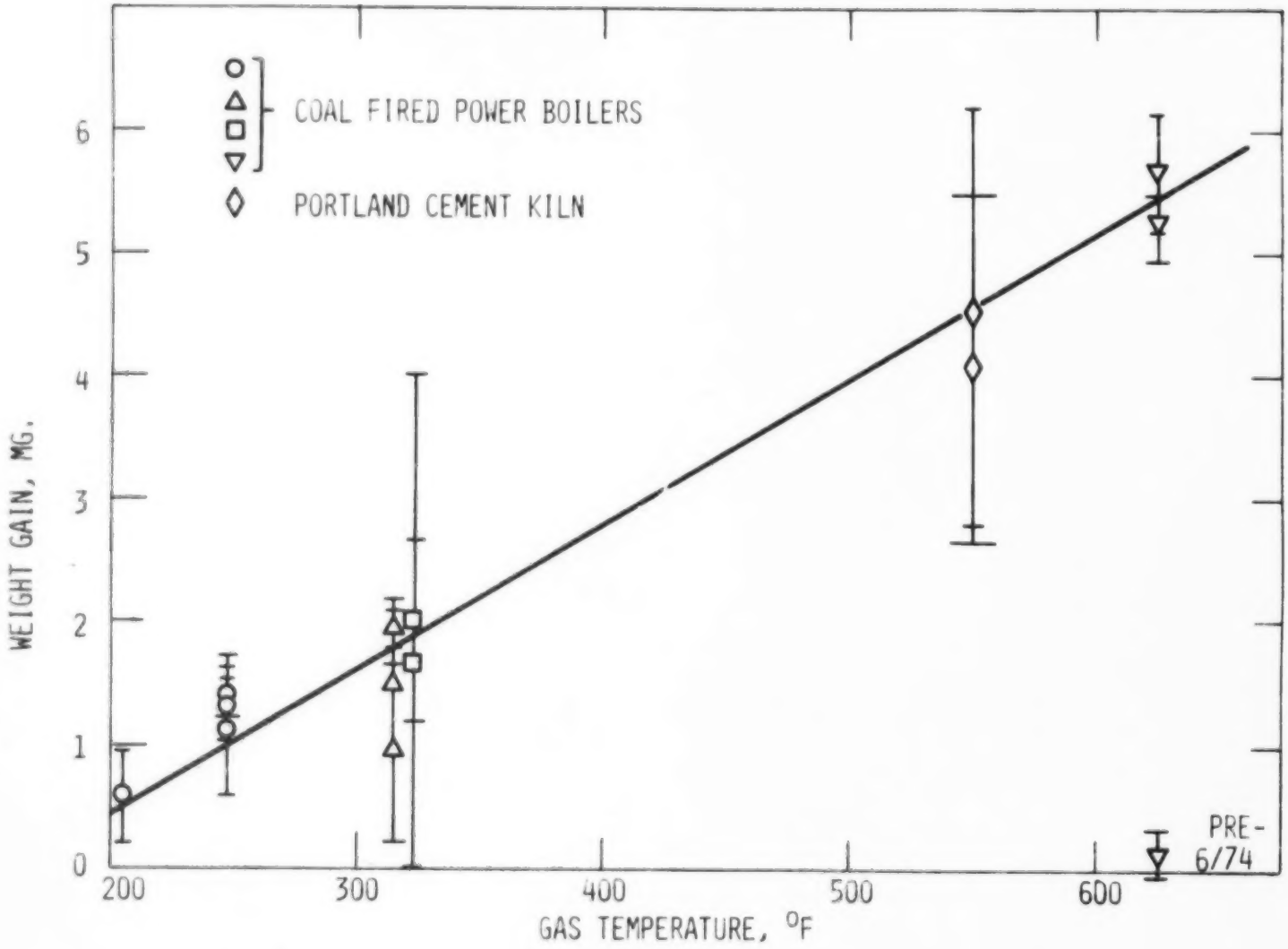


Figure 7-2. Anomalous Weight Increases of Andersen Glass Fiber Impaction Substrates at Different Flue Gas Temperatures.

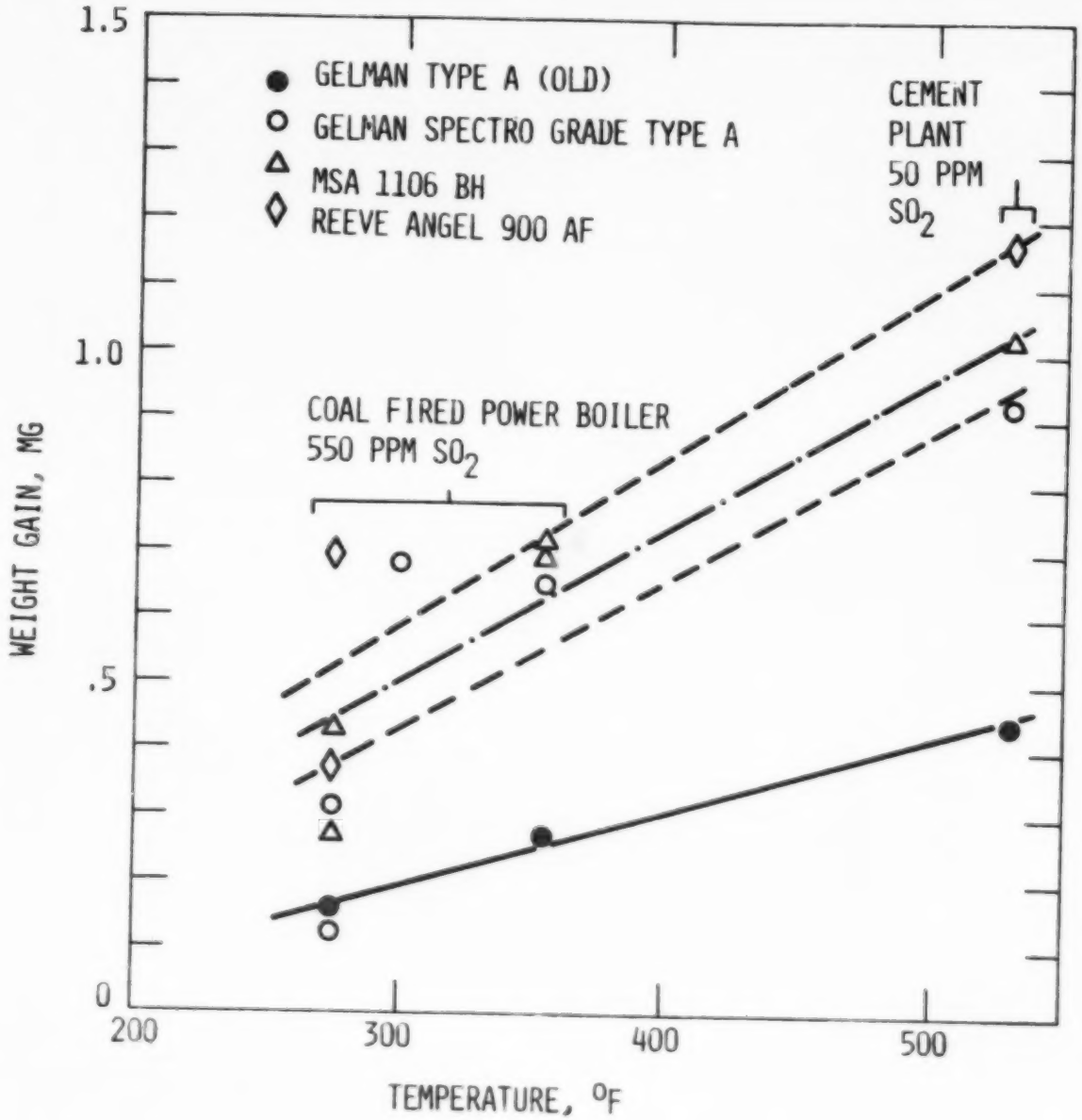


Figure 7-3. Anomalous Weight Gains of Various 47 mm Dia. Glass Fiber Filters at Different Temperatures. (60 minute samples at flowrates of 0.25 acfm).

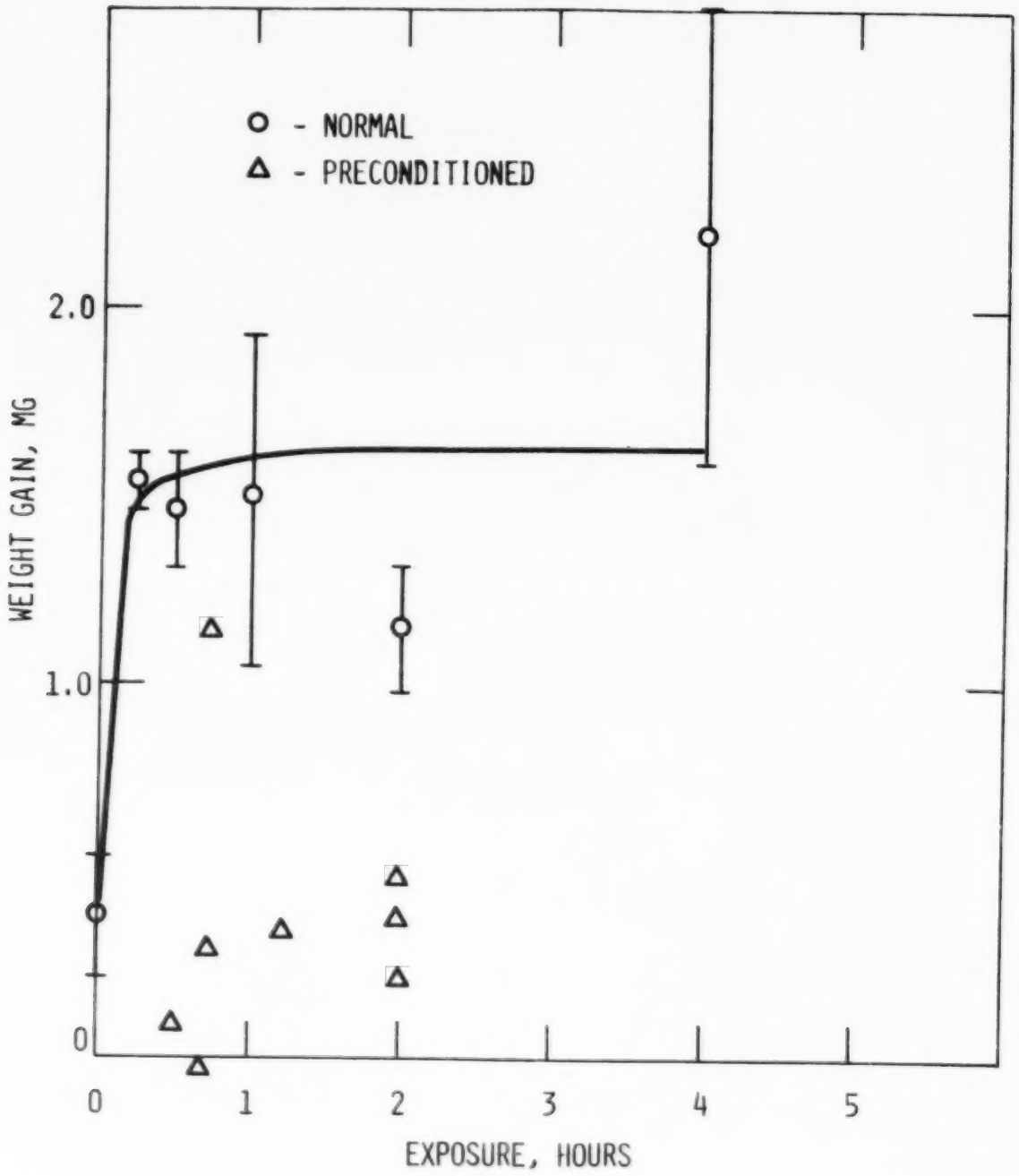


Figure 7-4. Anomalous Weight Gain of 64 mm Diameter Reeve Angel 900 AF Glass Fiber Filters.

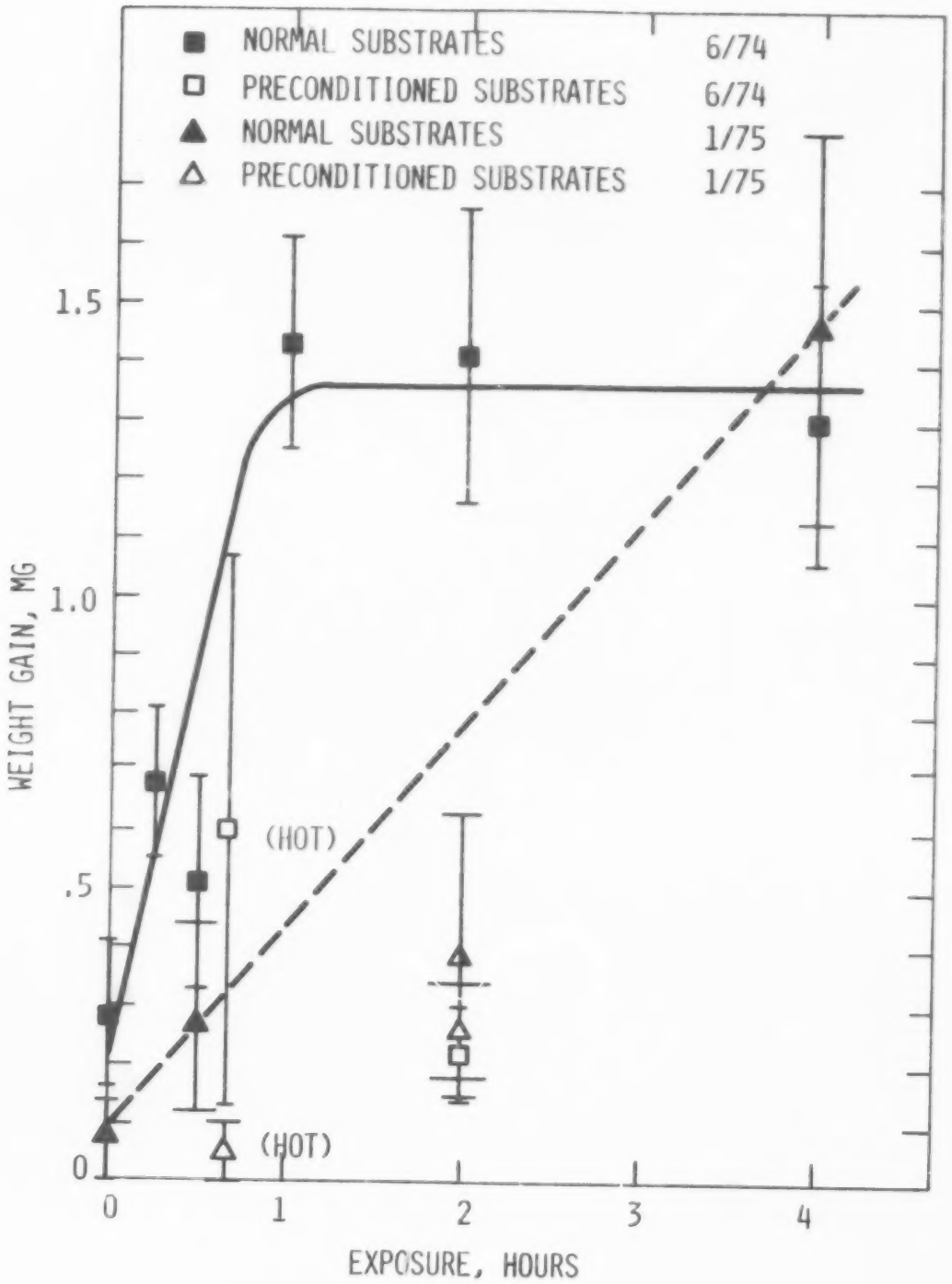


Figure 7-5. Anomalous Weight Gains of Andersen Impactor Glass Fiber Impaction Substrates.

Ten different types of filter media were tested at 2 industrial sites; the outlet of a hotside electrostatic precipitator on a cement kiln (Citadel), and the outlet of a coldside electrostatic precipitator on a coal fired boiler (Bull Run). The results of these tests are summarized as follows:

The pH of the filters varied widely from batch to batch before testing.

There was a definite correlation between high initial pH and weight gains upon testing.

The pH decreased during testing.

A large fraction of the weight gain in every case was found to be the result of sulfate formation on the filter media.

For a given temperature, the filters seem to "saturate" and not gain additional weight after a period of time (2-6 hours).

It is presumed the sulfate was formed by the reaction of sulfur dioxide with basic sites on the surface of the glass fibers. This is a phenomenon which was known to occur in ambient sampling, but which had been neglected or ignored in stack sampling.

Two approaches were attempted to avoid the problems of substrate weight gains. Substrates were preconditioned by long exposure to the flue gas so that most of the basic sites were neutralized before using them, and a search was made for substrate materials which do not react with the flue gas. Preliminary results indicate that preconditioning overnight reduces the magnitude of the anomalous weight gains by approximately a factor of ten. Also, in the tests to date, Teflon, Whatman GF/D and GF/A, improved quartz, and Reeve Angel 934 AH, are filter media which show little weight change when exposed to flue gas.

The detailed results of this work are reported in the Reports to Contract 68-02-0273. Work continued in an effort to reduce the interference to a more nearly tolerable level.

SECTION VIII
REFERENCES

1. Smith, W. B. and Jack R. McDonald. Calculation of Charging Rate of Fine Particles by Unipolar Ions. APCA Journal. 25(2), February 1975.

2. Leutert, G. and B. Böhlen. The Spatial Trend of Electric Field Strength and Space Charge Density in Plate Type Electrostatic Precipitators. Staub. 32(7), July 1972.

3. Gooch, J. P., Jack R. McDonald, and Sabert Oglesby, Jr. A Mathematical Model of Electrostatic Precipitation. EPA Report No. EPA-650/2-75-037, prepared under Contract No. 68-02-0265 by Southern Research Institute, Birmingham, Alabama. April 1975.

4. Forrest, J. and L. Newman. Sampling and Analyses of Atmospheric Sulfur Compounds for Isotope Ratio Studies. Atmospheric Environment. 7, 1973.

SECTION IX
CONVERSION FACTORS
(English to Metric Units)

Multiply	By	To Obtain
ft^3	0.0252	m^3
grains/ft^3	2.288	grams/m^3
feet	0.304	meters
inches	0.254	millimeters